Forest Research Report No. 169

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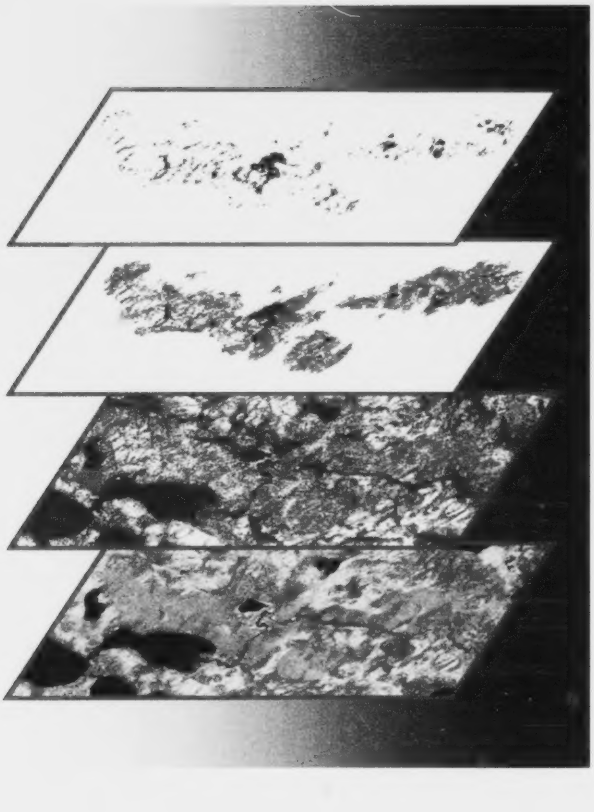
in relation to Ontario's policy directions for emulating natural forest disturbance



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2009

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Abstract

This study focused on assessing extent and variability of post-fire residual patches as relevant to directions in Ontario's *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide). We mapped 17 unsuppressed natural fires from northern boreal Ontario using IKONOS high resolution imagery. Satellite images were classified to identify burned as well as unburned land cover categories, and fire perimeters were derived using a fuzzy logic mapping technique. Residual areas in study fires were delineated using definitions for insular patches and peninsular patches as outlined in the NDPE guide. Extent of both residual types varied widely among the fires, and large fires contained more patches and higher patch extent. Most insular patches were very small, more common in fire interior, and appeared to be proximal to natural firebreaks. Insular patches were composed mainly of coniferous forest, shrubs, and wetland. Peninsular patch extent also varied widely among fires, with larger fires containing more patches, but not necessarily higher patch extent. No distinct spatial patterns of peninsular patches were associated with either fire geometry or natural fire barriers. These patches also were composed of coniferous forest, shrubs, and wetland. The NDPE guide direction's range for insular patch extent was well within the variability observed in our study fires, but overestimated the expected values in natural fires. The directions for spatial distribution of insular patches also matched the patterns observed within study fires. The NDPE guide direction's range for peninsular patch extent was well below the variability observed in the study fires, and greatly underestimated the expected values in natural fires. As well, the size threshold for insular patches that is imposed by the NDPE guide ignores a vast number of small patches, and thereby much of the extent of insular patch area that occurs in natural fires.

Resumé

La présente étude porte sur l'évaluation de l'étendue et la variabilité des peuplements résiduels après un feu, conformément aux directives contenues dans le document *Forest Management Guide for Natural Disturbance Pattern Emulation* (Guide NDPE). Nous avons recensé 17 feux naturels non éteints dans la forêt boréale du Nord de l'Ontario grâce à l'imagerie à haute résolution IKONOS. Les images satellites ont été classées afin de déterminer les catégories de superficie brûlée et non brûlée. Il a également été possible de calculer le périmètre des feux en utilisant une technique de cartographie à logique floue. Les zones résiduelles associées aux feux étudiés ont été délimitées selon les définitions de peuplements insulaires et péninsulaires, tel que précisé dans le Guide NDPE. L'étendue des deux types de peuplements résiduels varie grandement entre les feux : les feux majeurs comprennent beaucoup plus de peuplements et ces derniers sont beaucoup plus étendus que ceux des autres feux. La plupart des peuplements insulaires étaient très petits, plus courants dans les feux intérieurs et semblaient être à proximité des coupe-feux naturels. Les peuplements insulaires étaient principalement composés de conifères, d'arbustes et de marécages. L'étendue des peuplements péninsulaires variait également beaucoup entre les feux : les feux majeurs comportaient un plus grand nombre de peuplements, mais pas nécessairement d'une plus grande superficie, que ceux associés aux autres feux. Aucune tendance spatiale propre aux peuplements péninsulaires n'a été associée à la géométrie des feux, ni aux barrières naturelles. Ces peuplements étaient également composés de conifères, d'arbustes et de marécages. Selon le Guide NDPE, l'étendue des peuplements insulaires respectait la variabilité observée au cours des feux étudiés, mais les valeurs prévues pour les feux naturels ont été surestimées. Quant à la distribution spatiale des peuplements insulaires, elle correspondait aux tendances observées. Toujours selon le Guide NDPE, l'étendue des peuplements péninsulaires était bien en deçà de la variabilité observée au cours des feux étudiés, et les valeurs prévues ont été sous-estimées dans le cas des feux naturels. De plus, le seuil relatif à la taille des peuplements insulaires imposé dans le Guide NDPE ne tient pas compte d'un grand nombre de petits peuplements et par conséquent, de la majorité de l'étendue des peuplements insulaires après un feu naturel.

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We thank Rob Routledge and David White for their help with IKONOS image acquisition, Rob Luik and Rob Janser for providing fire information for the study fires, Simsek Pala for lending his expertise to image interpretation, and Trudy Vaittinen for graphics support. We are grateful to Joe Churcher and Mike Brienesse, who contributed to this study considerably by clarifying the directions in the Forest Management Guide for Natural Disturbance Pattern Emulation. Mike Brienesse assisted us further by providing analytical expertise for delineating peninsular residuals. As well, we thank the reviewers Mike Brienesse, Joe Churcher, Brad Ekstrom, Doug McRae, Roger Suffling, and Al Tithecott for their constructive comments on the draft report, which helped to improve its clarity.

Contents

Introduction

Background

Emulating natural disturbance has become a common forest management goal in disturbance-driven landscapes. As an example, Ontario's *Crown Forest Sustainability Act* (Statutes of Ontario 1995) emphasizes the principle of emulating natural forest disturbances and landscape patterns. This emphasis led to the development of forest management policies that guide forest harvest practices based on natural disturbance patterns. For example, the *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide, OMNR 2001), which has been applied in Ontario since 2003, specifies directions and provides standards and guidance to emulate fire disturbances. Included in this guide are specific directions about the amount of residual structure to be retained during forest harvest.

Following the release of the NDPE guide, Condition 39c of the Declaration Order MNR-71 (OEAB 2003) under the *Environmental Assessment Act*, specified that the Ontario Ministry of Natural Resources (OMNR) assess the effectiveness of the direction provided in that guide. As a result, a series of multi-scale scientific studies (described by Perera and Buse 2006) was initiated to improve understanding of characteristics of natural fire regimes in Ontario's fire-driven landscapes. These included studies focused on examining and reducing the uncertainties associated with the NDPE guide directions for leaving residuals at different scales: at the landscape-scale, the results of which are reported here, and at stand and tree-scale, reported previously by Perera et al. (2008).

Landscape-scale residuals, also referred to as residual patches, are live tree clusters or unburned areas within fire events (i.e., a discrete burn area). In Ontario, these include insular patches, which are disjunct from the fire's edge and thus truly within the fire event, and peninsular patches, which are protrusions of the surrounding unburned forest into the fire event (i.e., concave convolutions of the fire perimeter).

Our efforts to reduce the uncertainties associated with landscape-scale residuals were two-fold: first, we documented the state of published knowledge about post-fire residuals in boreal forests of North America, specifically as relevant to Ontario's NDPE guide directions (Perera et al. 2007), to assess the gaps in knowledge. While the published knowledge on post-fire residual patches provides some estimates of their extent and spatial variability, the standards used to define, assess, and quantify residual patches are inconsistent and sometimes ambiguous, making it difficult to generalize the information. As well, knowledge of the variability in occurrence, abundance, and spatial distribution of residual patches is limited even though this information is needed to develop specific management objectives and practices for broad natural disturbance emulation policies.

Thus, our second effort was to initiate a study to examine residual patches in unsuppressed fires to increase the understanding of their extent and spatial patterns in boreal Ontario.

Goal of this report

Improved understanding of the characteristics of post-fire residual structure in natural conditions will help forest policymakers to provide better strategic guidance for emulating natural fire disturbance patterns during forest harvesting, and forest managers to make better tactical decisions about retaining post-harvest residual structure to emulate fire disturbances. Thus, the objective of this report is to characterize the extent and variability of post-fire residual patch occurrence in natural boreal forest fire events to better understand their extent and spatial patterns.

Specifically, we examined unsuppressed fires in boreal Ontario to:

- Describe the extent and variability of residual patches within and among fire events
- Determine spatial patterns of residual patch occurrence within fire events

We relate these results to the directions provided in Ontario's NDPE guide (OMNR 2001).

Methods

Study area

The study area is in the northern-most part of the boreal forest region of Ontario that borders the boreal plains (Rowe 1972). Based on the classification of terrestrial ecozones and ecoregions of Canada (http://www.ec.gc.ca/soer-ree/English/Framework/Nardesc/borshd_e.cfm), it falls in the Lac Seul Upland (#90), Big Trout Lake (# 95), and Hayes River Upland (#89) ecoregions. Its vegetation is conifer-dominated boreal forest, characterized by a closed canopy of black spruce (*Picea mariana* [Mill.] B.S.P.), that is associated with white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* [L.] Mill.), and trembling aspen (*Populus tremuloides* Michx.). Drier sites are typified by open stands of jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* Michx.), and birch (*Betula* spp.) interspersed with black and white spruce. Poorly drained areas are covered by fens, bogs, and marshes and may contain low-growing, open stands of black spruce.

This area is contained within Ecoregion 2W (modified from Hills 1959 and follows 2002 version of Ontario's ecoregion map (http://www.mnr.gov.on.ca/MNR_E005108.pdf, p. 77). This area is very sparsely populated with sporadic small communities. Although this part of northern boreal Ontario is primarily Crown forest land, the area has not been managed for timber in the past, and only recently has become the focus of land management policies (http://www.ontla.on.ca/library/repository/mon/7000/10318518.pdf). Until 2004, the area belonged primarily to OMNR's extensive fire management zone, where fires are monitored and recorded but not actively suppressed, except in rare cases when a community is threatened (OMNR 2008).

Recurring wildfires are very common in this area. During the 1980s and 1990s, more fires have occurred and more area has burned in this part of Ontario than the remainder of the province (Perera et al. 1998). According to the three-dimensional definition of what comprise natural fires (Cui and Perera 2006), in this area fires can be considered as primarily natural because: (a) the probability of human-ignited fires is relatively rare – most fires would be lightning-ignited, (b) forest fuel types and their distribution are natural, not altered by humans, and (c) fires have not been actively suppressed.

We focused on areas in northern boreal Ontario where fires occurred during the six years prior to the start of the study. Our source of data, the IKONOS satellite imagery, is custom captured (see details below) and the focal areas for the study were selected to optimize the cost of satellite imagery acquisition. Based on information from OMNR's fire records, we selected 14 focal fire areas. Since our intent was to study patterns of natural fires, we ensured that these fires were lightning-caused, not suppressed, and occurred in an unmanaged forest landscape. The locations of the 14 focal fire areas are illustrated in Figure 1 in relation to Ontario's (a) ecoregions, (b) forest management zones in area of undertaking (AOU), and (c) fire management zones.

***Table 1**. Size and years of origin of study fires.[1] Details are provided in Appendix 1.*

OMNR code	Burn year	Fire size (ha)
NIP124	1998	200
NIP144	1998	500
NIP43	1999	1200
SLK82	1999	700
SLK5	2001	80
NIP72	2001	382
NIP73	2001	2250
SLK1	2002	2600
SLK2	2002	90
NIP48	2002	200
NIP47	2002	150
NIP32	2002	2600
RED34	2002	3070
RED56	2002	312
RED27	2002	4536
RED23	2002	4536
RED21	2002	3923
NIP38	2002	600
SLK55	2003	16,000
SLK80	2003	900

[1] Source: DFOSS fire archive access database, Rob Luik, Information Management Specialist, Ministry of Natural Resources, Fire Management Section, 70 Foster Drive, Sault Ste. Marie, ON (705-945-6748).

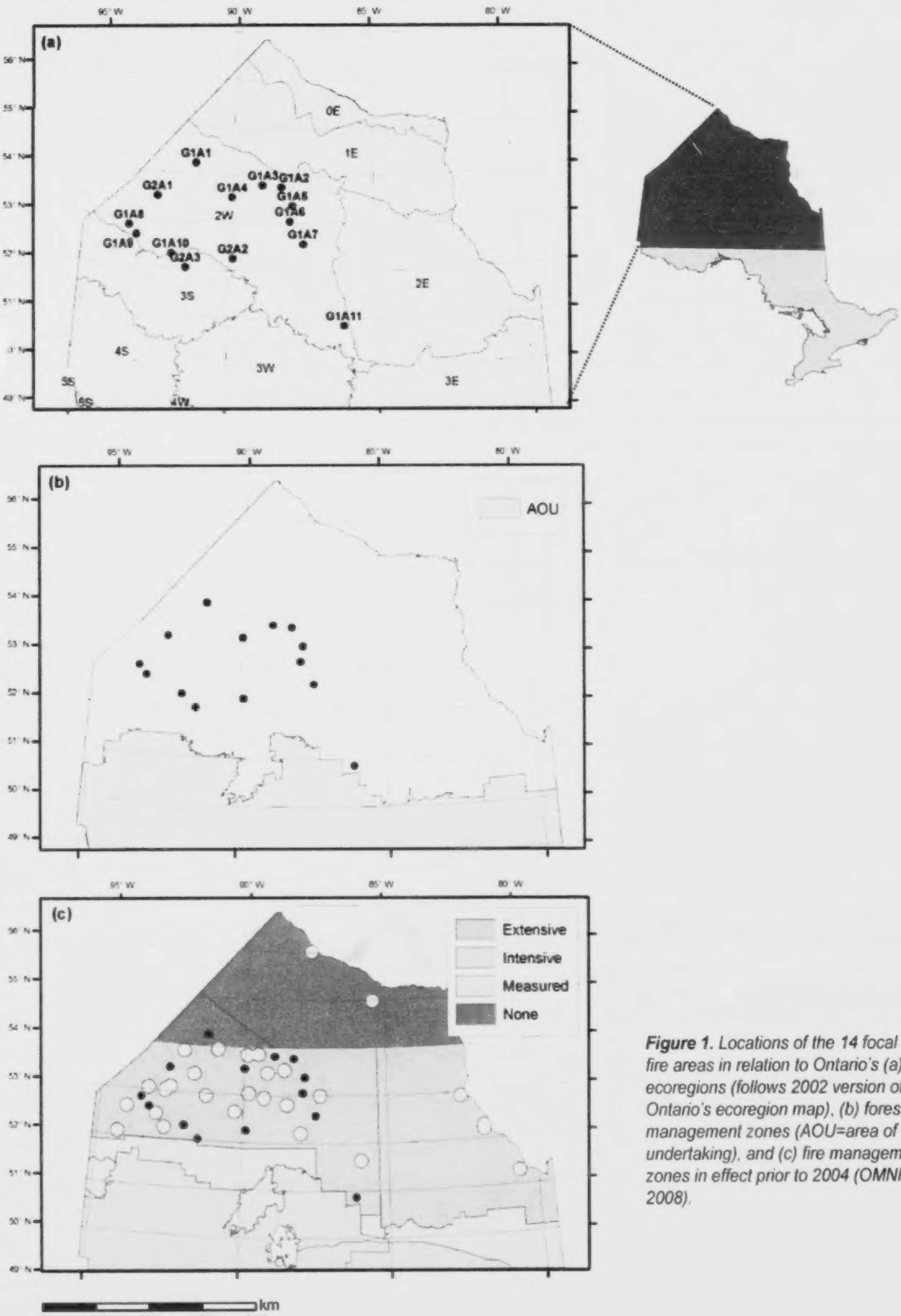


Figure 1. Locations of the 14 focal fire areas in relation to Ontario's (a) ecoregions (follows 2002 version of Ontario's ecoregion map), (b) forest management zones (AOU=area of undertaking), and (c) fire management zones in effect prior to 2004 (OMNR 2008).

Fires in these focal areas occurred from 1998 to 2003 under a range of fire weather conditions (characterized by various indices), and their recorded sizes ranged from 80 ha to over 16,000 ha as shown in Table 1 (for further details see Appendix 1). A cursory examination of the 45-year fire history of Ecoregion 2W showed that most study fires occurred in years when the annual area burned was relatively high (Figure 2).

Image capture and classification

We selected 14 IKONOS images that optimized the cost and the efficiency of coverage of fires in the focal areas. These images were acquired from Space Imaging Inc. (now GeoEye; http://www.geoeye.com/products/default.htm) during the summer of 2005 (June-August), to ensure the vegetation was leafed out in the far northern locations during capture dates (Table 2). Since images were purchased to capture specific areas and to avoid excessive cloud cover, image data were custom clipped such that each image represented different dimensions, and (based on OMNR fire polygons) some parts of fires were not captured by the images. The IKONOS data were supplied in GeoTIFF format, with each spectral band forming a unique file with geospatial reference information. All images were registered to the Universal Transverse Mercator (UTM) projection using the 1983 North American Datum (NAD83) in zones 15 and 16.

The base IKONOS data consisted of both geo-referenced panchromatic and multispectral 11-bit IKONOS imagery (Figure 3). The panchromatic band (450-900 nm) has a 1 m spatial resolution while the multispectral green (506-595 nm), red (632-698 nm), and near-infrared (757-853 nm) bands have 4 m spatial resolution. The blue band (445-516 nm) was not used in the data analyses.

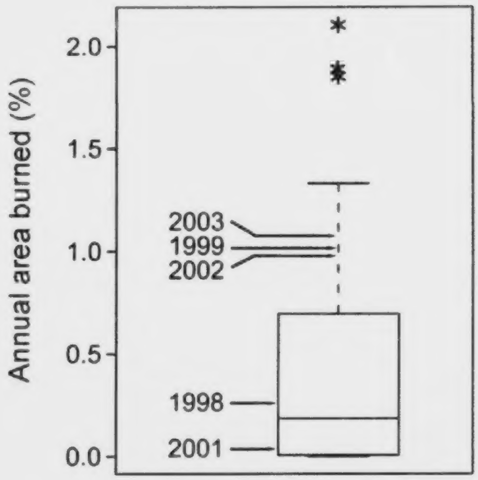


Figure 2. *Percentage annual area burned during the years (1998, 1999, 2001, 2002, and 2003) when study fires occurred, where the box indicates the interquartile range, line the median, and whiskers the min-max values during a 45-year period (1960-2005). The outliers are 1.5x interquartile range.*

Table 2. *Focal fire areas and details of corresponding IKONOS images.*

Focal fire area	Image capture date (2005)	Image area (sq km)
G1A1	June 07 and July 05	134.9
G1A2	June 15 and 23	118.8
G1A3	July 07 and 21	181.3
G1A4	June 07 and July 04	146.2
G1A5	June 15	158.0
G1A6	June 16 and 19	146.6
G1A7	June 15	112.7
G1A8	June 16 and 18	167.0
G1A9	June 16 and 21	117.7
G1A10	June 21	145.0
G1A11	June 17 and 20	116.4
G2A1	June 21	264.3
G2A2	July 07	219.2
G2A3	August 09	100.3

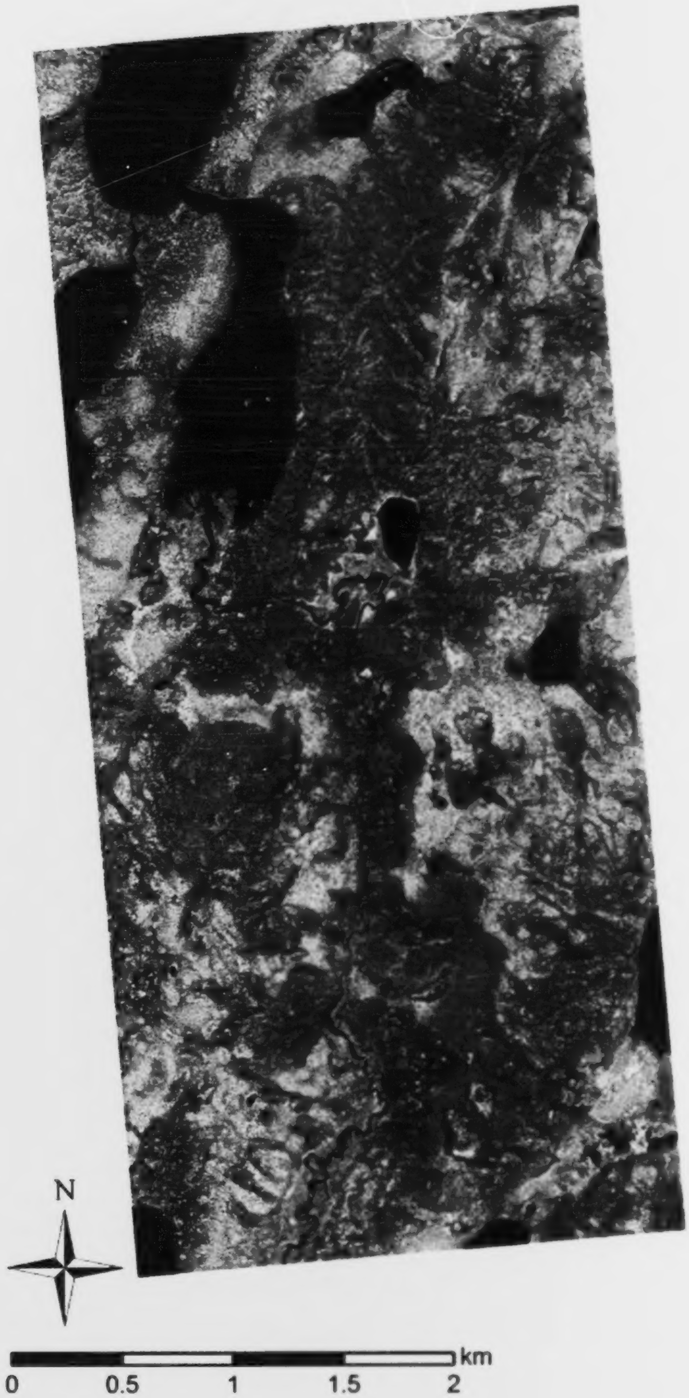


***Figure 3**. A false-colour infrared IKONOS multispectral image captured in June 2005.*

All image preprocessing was done with Erdas Imagine© software. The 1 m panchromatic and the 4 m multispectral bands were fused at 1 m spatial resolution to use the higher spatial resolution of the panchromatic band and the high spectral resolution of the multispectral bands. The multispectral bands provided the primary information for land cover types and vegetation characteristics and the panchromatic band was used to sharpen edges and provide additional local texture detail. No atmospheric correction was applied as each image was scrutinized by the relative reflection from the study targets under the given atmospheric conditions; it was not the intent to compare the spectral signatures among the images. Although the target classification for each image was the same, each image was classified independently using local signatures and training data.

IKONOS images were classified using a supervised image classification approach that required identifying and delineating training sites independently on each IKONOS image for specified land cover categories (Table 3). This was conducted as a regular land cover classification exercise, without any attempt to focus only on the fires. To ensure independence of classification, the image classification did not use any OMNR information (mapped fire boundaries, dates) about the fires within the image. This process required considerable visual interpretation of the imagery, and the image classifier's[1] extensive experience of over 30 years of image classification in northern Ontario forest landscapes. Spectral signatures were compiled from the training sites, indicating representative feature vectors for each land cover class across the study region. The definition of signatures was iterative where each land cover class was examined as a series of spectral subclasses to capture the full range of variability within each land cover type. Spectral signatures provided the typical spectral responses and their variability for each land cover class, so that a maximum likelihood classification algorithm could effectively assign the most probable land cover label to each image pixel.

Table 3. *Categories of land cover obtained from IKONOS image classification. These categories follow the classes of the 2000 Ontario Provincial Land Cover Database (OMNR 2005).*

Land cover category	Description
Complete burn*	Vegetated areas burned over their full extent, showing little or no evidence of vegetation.
Partial burn*	Vegetated areas burned over part of their extent, showing evidence of sparse or scattered vegetation.
Old burn*	Old burns where charring is still evident but regeneration appears.
Dense conifer	Dense, predominately coniferous forest which may include some minor component of deciduous species.
Sparse conifer	Sparse, predominately coniferous forest which may include some component of deciduous species.
Deciduous	Dense, predominately deciduous forest which may include some minor component of coniferous species.
Alder shrub woodland	Alder shrubs with some large trees occurring almost exclusively along watercourses.
Low shrub	Low shrub areas that may include grasses but do not support trees, found in proximity to lakes, on the deltas of watercourses, and on old burns.
Treed wetlands	Bogs and fens with tree cover.
Open wetlands	Bogs and fens without tree cover.
Water	Water bodies; includes some extensive string bogs.
Marsh	Inundated areas with emergent vegetation adjacent to water bodies.
Bedrock and non-vegetated	Areas with little or no vegetation, primarily bedrock outcrop.
Cloud and shadow	Image areas containing no usable data because of cloud and shadow effects.

*OMNR fire polygon information was not used in deriving burn cover categories during the image analyses.

[1]Simsek Pala, Spectranalaysis Inc; author of Ontario provincial land cover classifications 1975-2006.

IKONOS images were classified using a total of fourteen land cover themes, in parallel to the land cover classes (Table 3) in the 2000 Ontario Provincial Land Cover Database (OMNR 2005). They are:

Complete burn: Areas identified as burned over their full extent have a very dark, charred surface. Visual inspection of the image data reveals no colour or pattern indicative of residual vegetation. The degree of charred matter apparent suggests that these features were densely forested prior to the burn.

Partial burn: Areas identified as having been burned over part of their extent generally appear lighter than complete burns. The lighter appearance is attributed either to small residual patches of vegetation or to an open surface of sphagnum, lichens, or bedrock supporting a scattered distribution of vegetation. Where complete and partial burns occur in combination, each class is mapped individually.

Old burn: Older burns, which may themselves be less than 10 years old, still show spectral evidence of being burned but also show evidence of regeneration. Where the new vegetation has taken on the spectral character of forest, the feature is assigned to the appropriate forest class, even though the forest is young. Otherwise, the area is identified as an old burn to distinguish it from both more recent burns and other vegetation classes.

Dense conifer: This class designates areas densely covered with predominately coniferous forest that may include a minor component of deciduous species.

Sparse conifer: This class designates areas of sparse forest that have the distinctive appearance of conifer species but may, nonetheless, include some minor component of deciduous species. Some confusion is inevitable between dense treed bog and sparse conifer forest.

Deciduous: This class designates areas densely covered with predominately deciduous forest that may include some minor component of coniferous species. Dense deciduous forest is not extensive in these northern latitudes.

Alder shrub woodland: Alder shrub woodlands containing large trees occur almost exclusively along watercourses, where they are distinguished only with difficulty from deciduous forest.

Low shrub: Areas of low shrub growth, which may include grasses but do not support trees, are found near lakes, on the deltas of watercourses, and on old burns.

Open wetlands: This class designates bogs and fens with little or no tree cover and may include some small string bogs.

Treed wetlands: This class designates treed bogs and fens. The similarity in tree cover makes some degree of confusion between treed wetlands and sparse conifer forest inevitable.

Marsh: Marsh identifies areas that are either continuously, seasonally, or periodically inundated, have some emergent vegetation, and are adjacent to lakes and watercourses or at the deltas of watercourses.

Water: This class identifies water bodies and draws no distinction between clear and sediment-laden water bodies. It also includes some large string bogs (i.e., features comprising a large expanse of open water interrupted by a series of narrow, low, emergent peat ridges).

Bedrock and non-vegetated: This class designates areas supporting either no vegetation or only extremely sparse vegetation. Most occurrences of this class consist of areas of bedrock outcrop with minimal vegetation.

Cloud and shadow: This class serves to distinguish image areas that contain no usable data because of cloud and shadow effects.

Once images were classified, burn areas could be determined. Each burn area may contain one or more fire events, as recorded by OMNR, but that are indistinguishable from one another due to merging, re-burning, or errors in their original mapping. In some instances, partial clipping of fire events in IKONOS images may have occurred due to filtering for cloud cover and/or geo-referencing inaccuracies in OMNR fire data. Due to these reasons, as well as mapping method and data scale discrepancies between the OMNR fire records and our image analysis, the fire extents from the two data sources do not necessarily match. Due to cost and logistic restrictions, we could not undertake a ground truthing and error assessment exercise. However, spatial and classification errors were assessed by comparing against the original imagery as well as previous land cover classification results. Extensive manual editing based on visual interpretation was also required, especially to differentiate wetlands with surface water from shallow water bodies, or burn classes from forest classes with shadow effects.

The final classifications were filtered to 2 m spatial resolution, reflecting a 4 pixel minimum mapping unit (4 m^2). Some images (G1A2, G1A3, G1A5, G1A7, G1A8) were split (e.g., G1A2 to G1A2a and G1A2b) because they contained discrete burn areas either in space or time (different burn years), resulting in a total of 21 separate images with burn areas. The land cover images were resampled from 2 m to 8 m spatial resolution by implementing a non-overlapping block majority filter. This approach (Turner et al. 2000) enumerated the most frequent class within each unique larger block (8 m spatial resolution pixel) based on the underlying 4 m spatial resolution pixels and assigned that class to the coarser representation. The focus was to aggregate to a coarser spatial resolution similar to how a respective remote sensing device would view the landscape. This raster resolution was selected because it is the closest to the 1:20,000 cartographic scale (de Smith et al. 2007) typical for aerial photography-based mapping exercises associated with northern Ontario's forest management practices.

Deriving fire footprints

Burned areas comprise three primary groups of raster information: completely burned, partially burned, and unburned. Spatial arrangement of these burned (both completely and partially) and unburned pixels are inherently complex and the resulting geometry of the burns is fuzzy with few instances where the boundaries between burned and unburned areas are discrete, as a binary set of unburnt or burnt elements, rather they are mostly a gradient from unburned to burned, and vice-versa. As a result, the footprint of a fire must be delineated and interpreted as a gradient, rather than discrete or nominal boundaries, and boundaries between a burned and an unburned area are likely to be transition zones and not crisp single lines. Moreover, the recognition of such boundaries, whether discrete or continuous, is scale-dependent and changes with the spatial resolution of the analysis.

Our objective was to produce repeatable fire footprints and boundaries for each fire event at any given spatial resolution. To provide repeatable methods for delineating the fire footprint boundary, we reclassified the land cover classes to produce a binary set (completely or partially burned = 1; and all other classes = 0) for each pixel, at 8 m resolution. A 3×3 focal window was passed over the binary layers, and the focal sums were computed for each pixel (minimum = 0 when all 9 pixels are unburned, and maximum = 9 when all 9 pixels are burned). Low focal sums indicate less contiguous clusters of burned pixels, whereas high focal-sum values indicate burned pixels surrounded by many other burned pixels. All pixels with a value >0 (which exhibits some probability of fire membership) were coded 1, and vectorized to produce polygons that represent the fire footprint. A 1-ha filter was applied to eliminate external noise polygons prior to re-rasterizing. For details, see Remmel and Perera (in press).

Once the fire footprint and the external fire event boundaries are identified, many geometrical properties of those burn areas can be determined, at any given spatial resolution. These properties include:

- Spatial coordinates of the fire event boundary
- Fire event size
- Complexity of fire boundary and peninsular residual patches
- Extent and spatial position of insular residual patches

Defining residual patches

OMNR's definitions of residual patches, both insular and peninsular, are based on both size and location in relation to the disturbance area perimeter (OMNR 2001). We based our delineation and categorization of insular and peninsular patches on the OMNR definitions, and used step-wise filtering criteria to determine the residual patch entities (Figure 4). Additional compositional and structural criteria are associated with post-harvest residuals (e.g., stocking density, tree heights) in the OMNR definitions that we could not apply here due to limited information in IKONOS data. For the purposes of this study, insular and peninsular residual patches are defined as follows:

Insular residual patches are clusters of unburned pixels:

(a) Composed primarily of treed land cover classes (dense conifer, sparse conifer, deciduous, and alder and shrub woodland, containing other vegetated land cover classes (low shrub, treed wetland, open wetland, and marsh);

(b) Area of above cover classes greater than or equal to 0.25 ha; and

(c) At least 20 m away from the fire perimeter

Peninsular residual patches are:

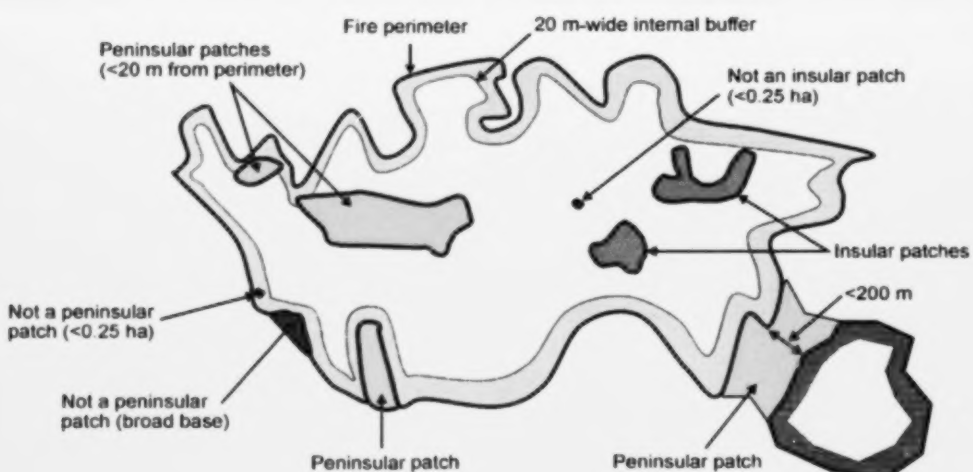
(a) Unburned pixels (outside the fire footprint) that comprise the parts of the fire perimeter that extends inwards, with a base less than 400 m (for fires ≤ 260 ha) or 1000 m (for fires > 260 ha), and longer than its base width; and

(b) Residual patches that meet all criteria for insular residuals, but are less than 20 m from the fire perimeter.

(c) Isthmuses, which are polygons of unburned forest that occur between two disjunct burn polygons within the same fire footprint (<200 m wide at the narrowest point and connected to the surrounding forest).

Residual patch definitions

Residual patch definitions used in this study are as per the *Forest Management Guide for Natural Disturbance Pattern Emulation* (OMNR 2001). For those not familiar with this guide, a schematic of insular (green) and peninsular (orange) residual patches for a hypothetical fire event is given here. Where interpretation of the definitions was required to develop repeatable, quantifiable parameters for our analyses, policy experts Joe Churcher and Mike Brienesse (OMNR 2008, pers. comm.) provided final interpretations. (For more specific details see Figures A1 and A2 on page 27 of the NDPE guide; OMNR 2001).



To derive the patches, we first identified all unburned pixels within a fire footprint and determined whether they contained burnable cover.[2] Those with burnable cover that occurred in clusters, i.e., not individual pixels, were considered patches. This provided an estimate of all residuals within a fire footprint. If these clusters were at least 0.25 ha they were considered patches as per OMNR's definition (OMNR 2001). Clusters that met the minimum size criteria and occurred ≥20 m from the perimeter of the fire footprint were deemed insular patches. This process is illustrated in Figure 4.

Two types of peninsular residual patches are recognized by OMNR: protrusions of the disturbance area perimeter, that conform to width and breadth dimensions outlined in the NDPE guide, and spatially delineated and classified by the NDPEG tool (Elkie et al. 2002), hereafter referred to as Type 1 peninsulars, and the insular patches that are larger than 0.25 ha and occur within 20 m of the fire footprint perimeter, referred to as Type 2 peninsulars (Figure 4).

Type 1 peninsular patches (protrusions of perimeter) were estimated using (a) the NDPEG tool, (b) expert advice, and (c) adapting harvest residual compositional criteria (Figure 5). NDPEG tool is a software package developed by OMNR to assist planning teams in implementing the natural disturbance emulation guide (OMNR 2001). Using the disturbance perimeter, it clusters disturbance areas and applies various spatial criteria (Figure 5) to determine candidate peninsular residual patches (for details of these procedures, see Elkie et al. 2002). These candidate areas were further filtered by an expert (M. Brienesse, OMNR, pers. com., 2008) to simulate the post-NDPEG tool selection process that occurs during application of OMNR's guide directions. The selection process involved visual inspection of each candidate peninsula for quality, which determines whether they are included as peninsular residuals. A visual inspection was necessary due to a lack of an automated process to reliably assess the width and depth of complex shapes. Complex shapes include multi-fingered peninsula, hook shaped peninsula, and isthmuses (polygons of unburned forest that occur between two disjunct burn polygons within the same fire footprint (<200 m wide at the narrowest point and connected to the surrounding forest). As it was not possible to evaluate the width to depth ratio of an isthmus, all isthmuses were considered high quality. Finally, the peninsular patches were screened to meet the compositional criteria of OMNR's definition. Since the specific stand criteria (forest cover types, stocking density, and tree heights, as per OMNR 2001) were not available in our data, we selected patches composed of burnable cover and at least 0.25 ha.

[2]We considered all forested and vegetated classes as burnable. Wetland classes were included as well because they may burn under extreme drought conditions.

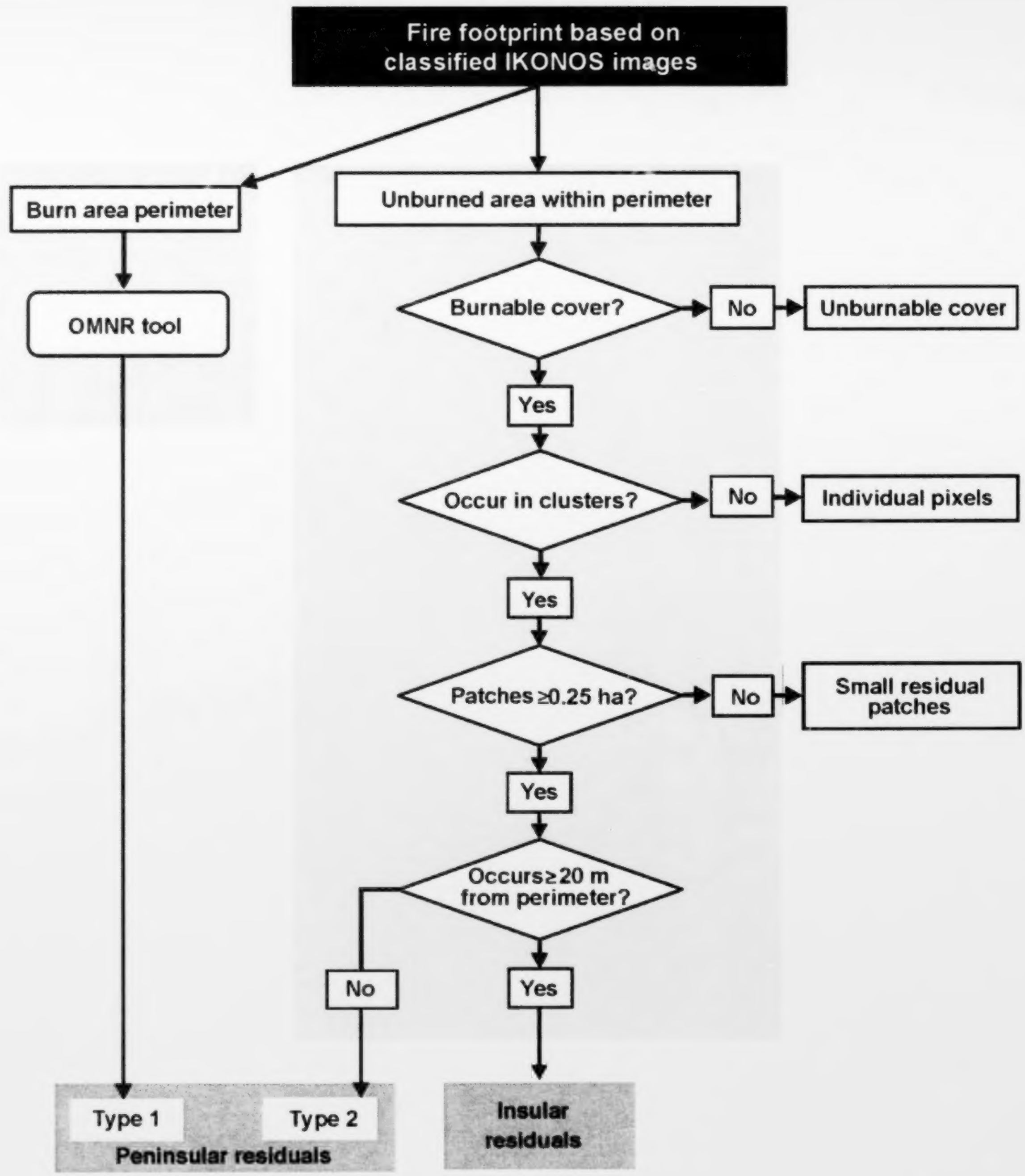


Figure 4. *Stepwise criteria used to determine insular and peninsular residual patches for fire footprints (derivation of peninsular residual patches is detailed in Figure 5).*

Figure 5. *Stepwise process used to determine Type 1 peninsular residual patches for fire footprints (Source for steps (a) and (b): M. Brienesse, OMNR, 2008).*

Results

Fire footprints

Footprint area

Land cover classifications of IKONOS images contained 14 cover classes (see methods for details), including categories for partial burn and complete burn. While the exact composition varied among image areas, all contained contiguous areas of burned land cover. Figure 6 illustrates the classified IKONOS image G1A2a as an example to show the level of detail and variability in cover types across an image.

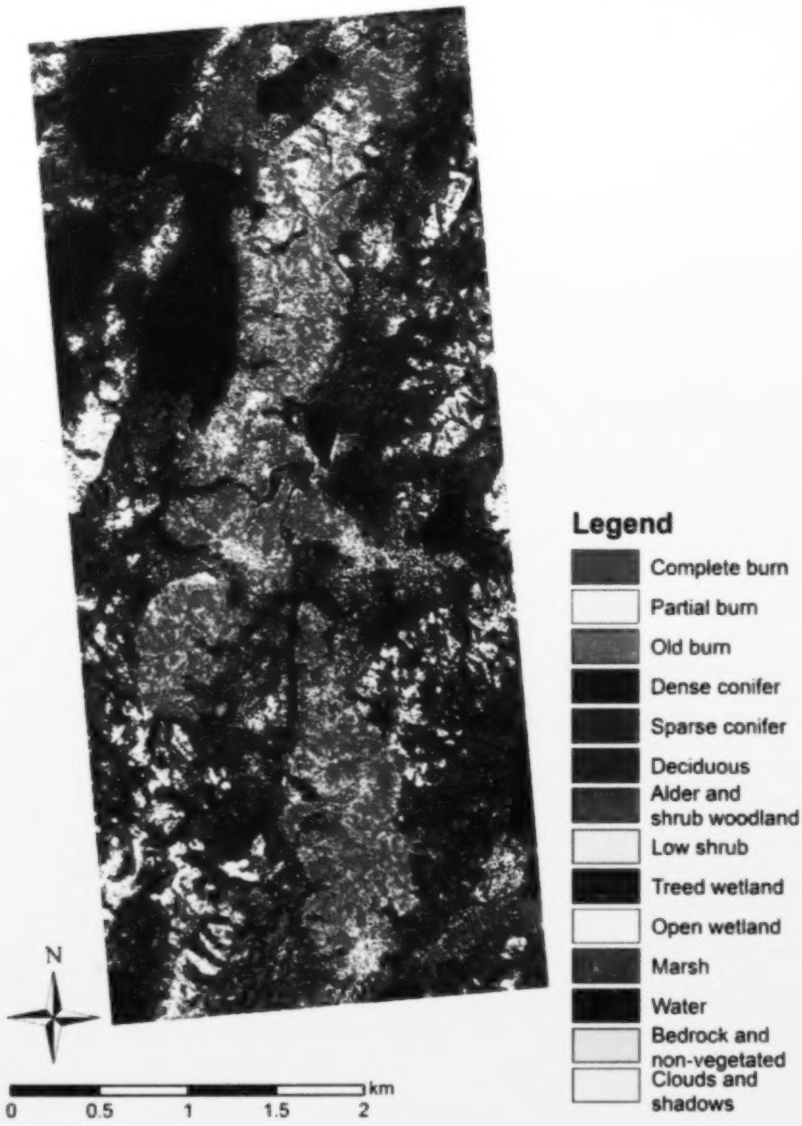


Figure 6. Land cover classification of IKONOS image G1A2a (See methods for details of the land cover classes.)

Four IKONOS images had to be eliminated from further analyses. These included an image (G1A4) that contained data only on part of the burn area (due to geo-referencing errors that occurred during image acquisition), and three images (G1A7b, G1A10, and G2A1) that contained excessive cloud cover (which interfered with derivation of fire footprints). The remaining 17 fire footprints were assigned sequential codes (FF-1 to FF-17) for identification purposes (Table 4).

***Table 4**. The study fire footprints, corresponding focal fires areas in IKONOS images, and OMNR fire information.*

Fire footprint code	Focal fire area	Fire footprint extent (ha)	OMNR fire record [4]	
			Fire code	Burn area (ha)
FF-1[1]	G1A1	4525.3	SLK 1, SLK 2, SLK 5	2770
FF-2	G1A2a	306.7	NIP 72	382
FF-3	G1A2b	1058.0	NIP 43	1200
FF-4	G1A3a	492.8	SLK 82	700
FF-5	G1A3b	80.6	NIP 48	200
FF-6	G1A3c	80.5	NIP 47	150
FF-7	G1A3d	163.8	NIP 124	200
FF-8	G1A5a	2129.1	NIP 73	2250
FF-9	G1A5b	1574.9	NIP 32	2600
FF-10[2]	G1A6	2286.1	RED 34, RED 56	3382
FF-11	G1A7a	701.6	NIP 144	500
FF-12	G1A8a	3741.8	RED 27	4536
FF-13	G1A8b	940.5	RED 23	4536
FF-14	G1A9	3072.2	RED 21	3923
FF-15	G1A11	57.7	NIP 38	600
FF-16[3]	G2A2	3276.9	SLK 55	16000
FF-17	G2A3	719.3	SLK 80	900

According to OMNR fire records, [1] SLK 1 and SLK 2 are overlapping burns that reburned SLK 5; [2] RED 34 and RED 56 are merged burns; [3] only some fire polygons of SLK55 were mapped by IKONOS imaging; and [4] Source: Fire Perimeter Archive, Rob Luik, Information Management Specialist, Ministry of Natural Resources, Fire Management Section, 70 Foster Drive, Sault Ste. Marie, ON (705-945-6748).

The fire footprints (defined as the area within the most probable locations of the outer fire boundary) within the classified images, derived at 8 m spatial resolution, are illustrated using FF-2 and FF-3 as examples (Figure 7a,c). Fire footprint extents ranged from 57.7 ha (FF-15) to 4525.3 ha (FF-1), with eight fire footprints greater than 1000 ha and three smaller than 100 ha. These footprints are often composed of multiple polygons of burn areas, and generally corresponded to the shapes of OMNR's mapped fires (as shown in Figure 7b,d). In some instances, discrepancies existed between the derived fire footprints and OMNR's fire maps due to differences in methodological details of mapping the boundaries as shown with the example FF-3 (Figure 7c,d). Fire footprints derived for all 17 fires using IKONOS images are provided in (Figures 14-30).

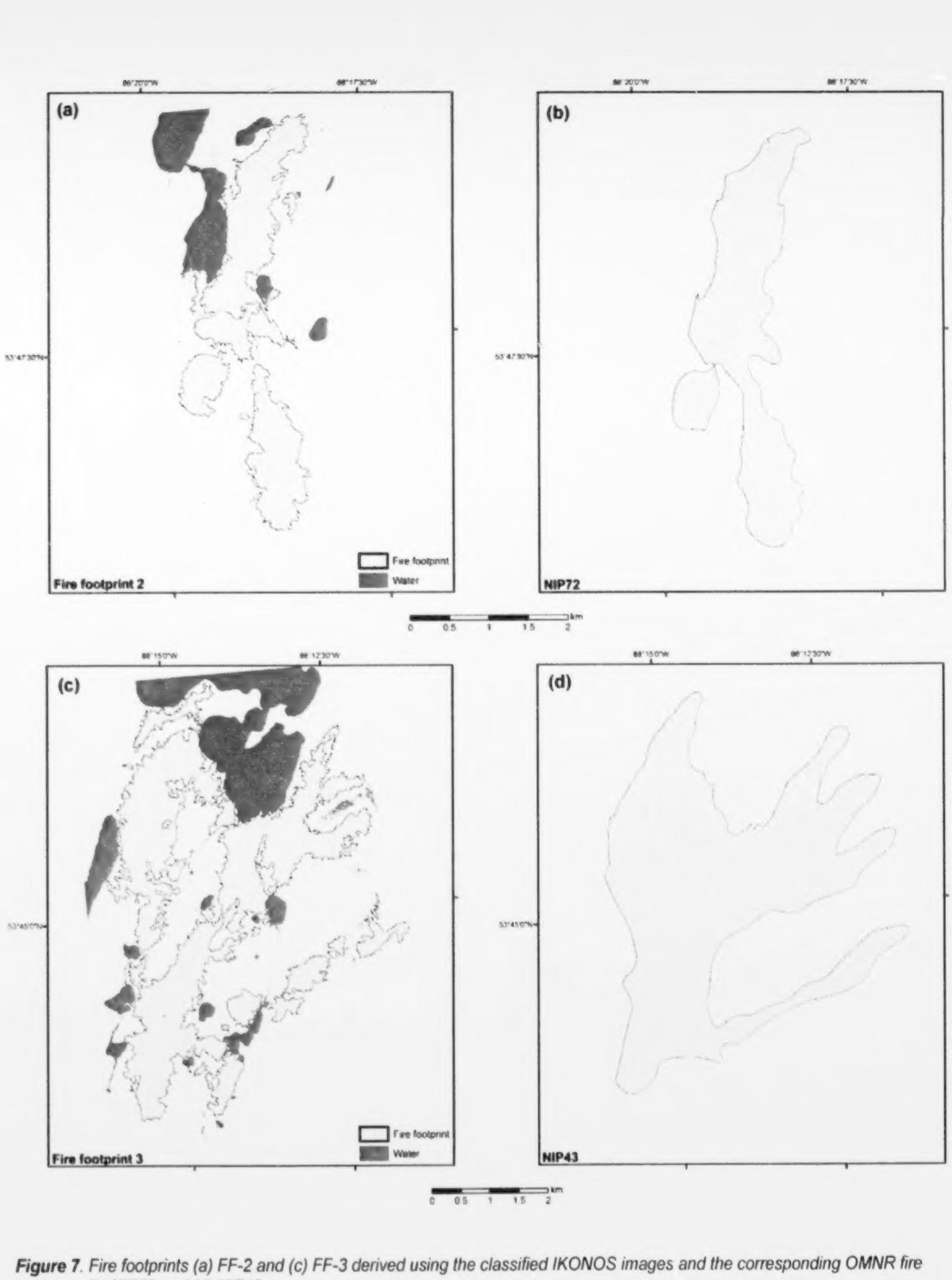


***Figure 7**. Fire footprints (a) FF-2 and (c) FF-3 derived using the classified IKONOS images and the corresponding OMNR fire polygons (b) NIP72 and (d) NIP43.*

Residual area

While the burned area (partial burn and complete burn land cover categories) dominated, many other unburned land cover types also occurred within the fire footprints, as shown in the example of fire footprint FF-2 (Figure 8).

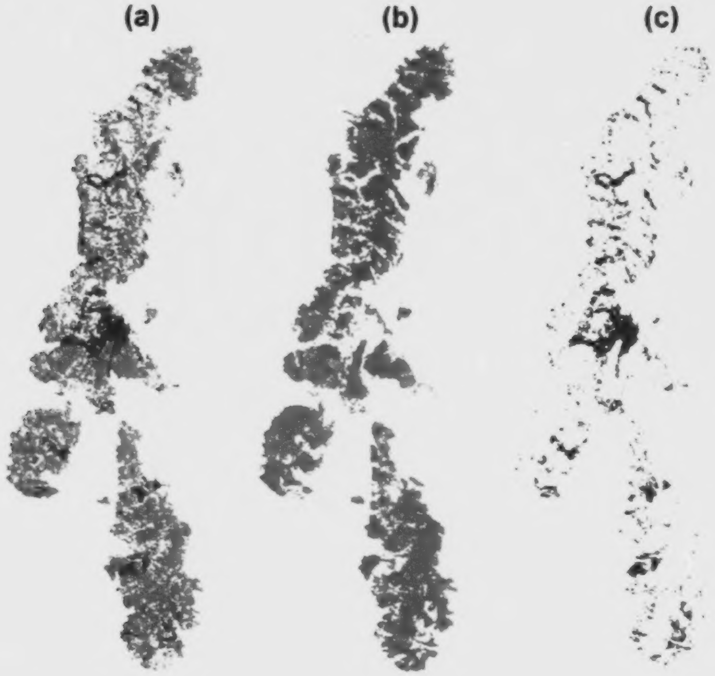


Figure 8. Fire footprint of FF-2 and its (a) primary land cover categories: purple= unburned (vegetated, bedrock, and water); red=completely burned; and yellow=partially burned. (b) burned area (partially + completely) and (c) unburned area (vegetated, bedrock, and water).

These included potentially burnable land cover types (readily burnable as well as that may burn during extremely dry weather) as well as unburnable land cover types (will not burn even during the driest possible weather) such as water bodies and bedrock (Table 5).

We considered the potentially burnable cover types, composed of forest (dense conifer, sparse conifer, and deciduous), shrub (alder, shrub woodland, and low shrub), and wetlands (treed, open, and marsh), as the residual cover. Some over- or underestimation of the burnable extent is possible because the cover types occurring under cloud cover in the IKONOS images (averaged 1.5% of image area) could not be determined. Also, in some cases the burnable area may be overestimated because wetland and marsh cover may not burn except during extremely dry weather.

Table 5. The total unburned area (ha) of study fire footprints and the area of potentially burnable cover. See text for descriptions of the unburnable and potentially burnable cover types.

Fire footprint	Unburned area within fire footprints (ha)		
	Total unburned area	Unburnable cover types	Potentially burnable cover types
FF-1	1466.7	228.5	1238.2
FF-2	57.9	1.9	56.0
FF-3	317.2	2.0	315.2
FF-4	167.2	0.5	166.7
FF-5	20.7	0.0	20.7
FF-6	17.0	0.0	17.0
FF-7	44.6	0.0	44.6
FF-8	387.6	2.0	385.6
FF-9	341.9	16.6	325.3
FF-10	720.8	170.2	550.6
FF-11	265.4	39.6	225.8
FF-12	1634.0	195.0	1438.9
FF-13	287.0	44.1	242.9
FF-14	1212.5	481.9	730.6
FF-15	11.2	0.0	11.2
FF-16	945.7	187.2	758.5
FF-17	105.3	14.9	90.4

We expressed the residual extent as a percentage of the burnable, not the total, footprint area. This is because the total footprint area contains unburnable cover, which in some cases (e.g., FF-14, Table 5) may represent a large part of the area. Figure 8 shows the extent of burnable residual area within fire footprints obtained at different stages of applying the sequential filter described in Figure 4. The average decrease from total residual area to area of residual clusters (minimum 2 pixels or 0.0128 ha) was 1.9±0.1%; and from area of residual clusters to area of residual patches (minimum ≥0.25 ha) was 8.5±0.5%. This decrease was considerable especially for small fire footprints such as FF-6 and FF-15. This indicates the importance and effect of the various definitions of residual area on patch number/patch area results and why comparisons among studies are difficult to impossible.

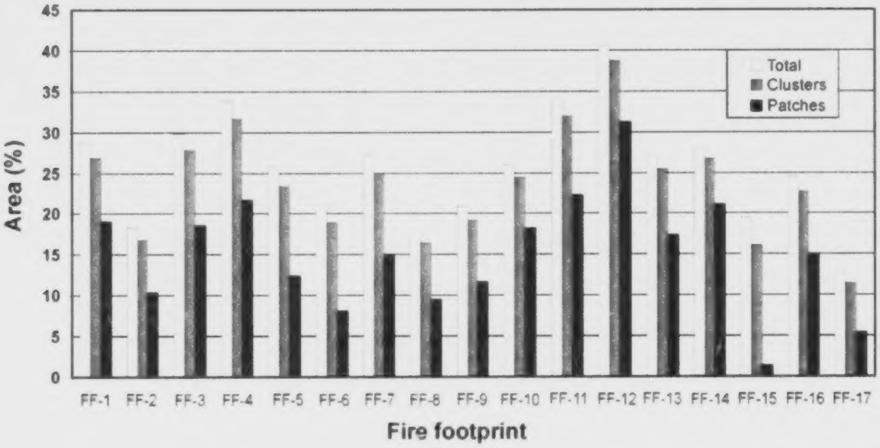


***Figure 9**. Extent of residuals within fire footprints as a percentage of the burnable area (total footprint area - unburnable area). Total = burnable residual area; clusters = residual area in ≥2 pixel clusters; patches= residual area clusters ≥0.25 ha.*

Extent of residual patches

We broadly defined the residual patches as spatial clusters of potentially burnable land cover types that occurred within unburned areas inside fire footprints. In principle, translation of this definition to spatial information is simple: residual patches are spatially correlated clusters of unburned pixels, within the fire perimeter, and are composed of forest cover. In practice, however, given the gradients in their characteristics, such as porosity (proportion of burned pixels within clusters), size (from 2 pixels to many), and composition (dense forest to wetland) definition of post-fire residual patches is a complex matter. These factors as well as the spatial resolution of the analyses (e.g., pixel size, search window radii), make it difficult to delineate residual patches objectively and in a repeatable automated manner. This problem is avoided in reports of residual patches in literature by authors resorting to subjective definitions and manual delineation (Perera et al. 2007). As well, this is reflected in the many different definitions of insular residual patches present in the literature, which vary widely based on specific goals of studies and policies (Table 6).

Peninsular patches, which result from the complexity of fire shapes, and their deviation from Euclidean shapes, are addressed only by OMNR (2001) and Perron (2003), who used OMNR's definitions.

Table 6. *Definitions of residual patches reported in literature. OMNR's definitions, which were applied in this study, are shaded.*

<table>
<tr><th>Insular residual patches</th><th>Peninsular residual patches</th></tr>
<tr><td>"Small"
(Scotter 1972, Novak et al. 2002)</td><td rowspan="4"><400 m base for fires <260 ha and 400-1000 m for fires >260 ha
(Perron 2003, based on OMNR 2001)</td></tr>
<tr><td>≥0.1 ha
(Perron 1983)</td></tr>
<tr><td>≥1 ha
(Eberhardt and Woodard 1987, Kafka 2001)</td></tr>
<tr><td>≥1 ha and ≥20 m wide
(Smyth 1999)</td></tr>
<tr><td>Small patches (<10 ha) and large patches (>100 ha)
(Shieck and Hobson 2000)</td><td>≥0.25 ha;
400 m base for fires <260 ha and 400-1000 m for fires >260 ha</td></tr>
<tr><td>≥0.25 ha;
≥20 m away from the disturbance edge</td><td>≥0.25 ha;
<20 m away from the disturbance edge</td></tr>
</table>

Insular residual patches

The insular residual patch (as per OMNR's definition: minimum area ≥0.25 ha *and* ≥20 m from the fire footprint boundary) extent ranged from 0.0% (FF-15) to 11.7% (FF-12) across fire footprints at 8 m spatial resolution, with an overall mean of 3.6 ±0.7 and a 93.5% coefficient of variation. All but two fire footprints had less than 5% insular residual patch extent. Figure 10 illustrates insular residual patches in fire footprints, using FF-2 and FF-3 as examples. The proportional decrease from total residual patches (≥0.25 ha) to insular residual patches (≥0.25 ha *and* ≥20 m) was substantial at 78.2±4.1% overall. In some fire footprints (FF-4, FF-5, FF-6, FF-7, and FF-11) this decrease was over 90%, and in the smallest footprint (FF-15) it was 100%. Overall, there were 1007 insular residual patches across the 17 fire footprints. Number of insular patches per fire footprint ranged from 0 (FF-15) to 259 (FF-1), with a mean of 59±17 and a coefficient of variation of 120%. The maximum patch size ranged from <1 ha (three fire footprints) to 97.1 ha. Only five fire footprints had mean patch sizes >1 ha; all but four fire footprints had median patch sizes <0.5 ha (Table 7).

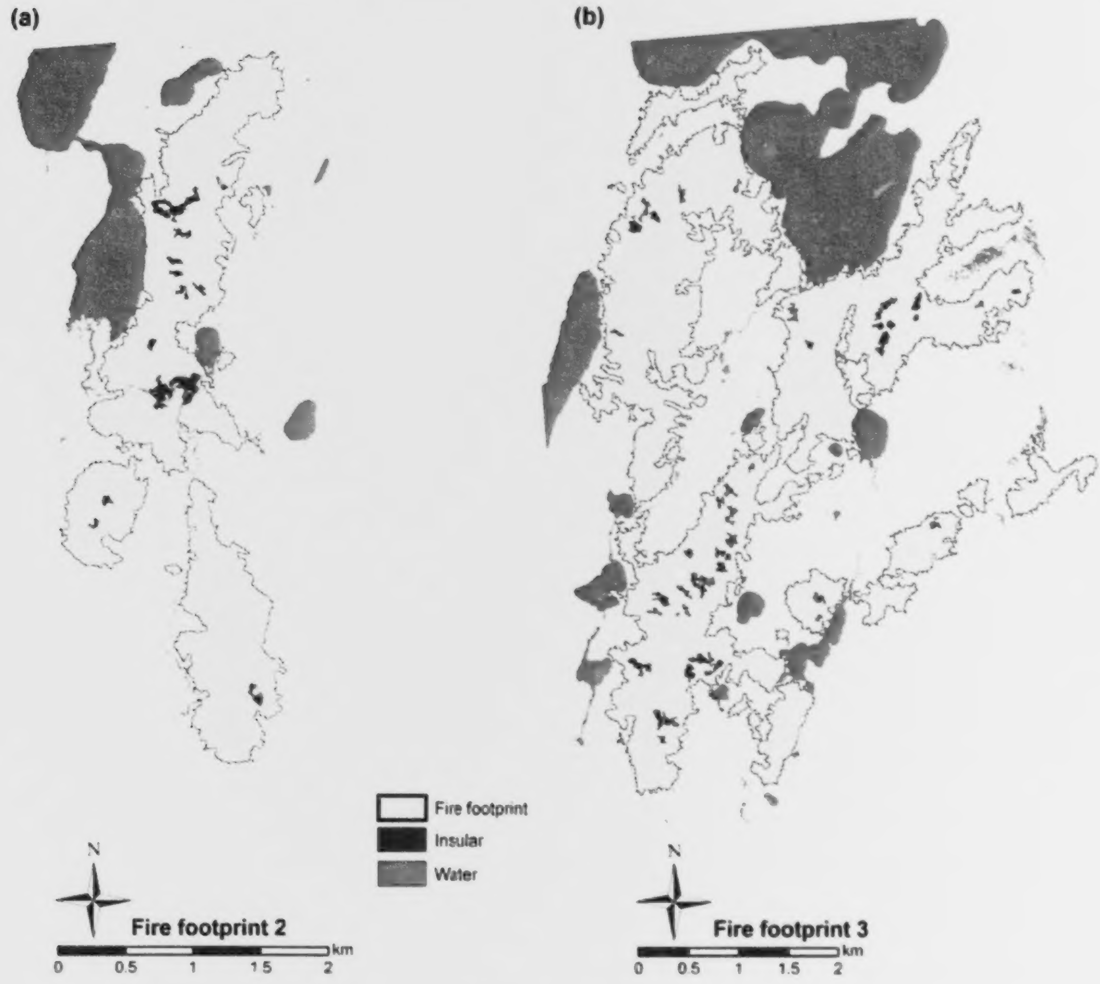


Figure 10. *Insular residual patches within fire footprints (a) FF-2 and (b) FF-3.*

Table 7. *Insular residual patch extent, number, and variability within the study fire footprints.*

Fire footprint	Residual patch area (%)	Number of patches	Patch size (ha)					
			Maximum	Median	Mean	Standard error	95.0% confidence limit	
							Lower	Upper
FF-1	7.15	259	56.9	0.45	1.19	0.26	0.68	1.69
FF-2	3.33	14	2.5	0.36	0.73	0.20	0.29	1.16
FF-3	2.63	46	1.8	0.47	0.60	0.05	0.49	0.71
FF-4	1.49	14	1.5	0.34	0.52	0.09	0.31	0.74
FF-5	1.16	2	0.6	0.47	0.47	0.09	0.00	1.69
FF-6	0.76	1	0.6	0.61	0.61	0.00	0.61	0.61
FF-7	0.25	1	0.4	0.41	0.41	0.00	0.41	0.41
FF-8	2.94	84	7.1	0.48	0.75	0.10	0.54	0.94
FF-9	2.78	57	7.3	0.42	0.76	0.15	0.46	1.06
FF-10	10.60	109	97.1	0.49	2.06	0.89	0.29	3.83
FF-11	0.75	7	1.6	0.57	0.71	0.16	0.33	1.11
FF-12	11.74	192	76.4	0.52	2.17	0.49	1.20	3.14
FF-13	6.90	29	44.9	0.37	2.13	1.53	0.00	5.27
FF-14	8.33	91	76.0	0.56	2.37	0.93	0.52	4.23
FF-15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FF-16	1.79	90	2.5	0.48	0.62	0.04	0.53	0.70
FF-17	0.86	11	1.8	0.38	0.55	0.15	0.22	0.88

Insular patch sizes ranged from a minimum of 0.25 ha (<0.25 ha patches were excluded given OMNR definition) to a maximum of 97.1 ha, with a mean patch size of 1.44 ha (95% confidence interval of the mean patch size ranged from 1.09 ha to 1.79 ha). Most insular patches were small, with a median of 0.47 ha, and over 80% of the patches were smaller than 1 ha. Among all patches, only 10% were larger than 2 ha, and 1% were larger than 20 ha. The frequency distribution of insular patches within each fire footprint are skewed left and even in fire footprints with larger insular patches (e.g., FF-10, FF-12, FF-13), most patches were <1 ha.

Number of insular patches within fire footprints increased with extent of potentially burnable area (Figure 11a). As well, the insular patch area as a percentage was significantly correlated with potentially burnable area (Figure 11b).

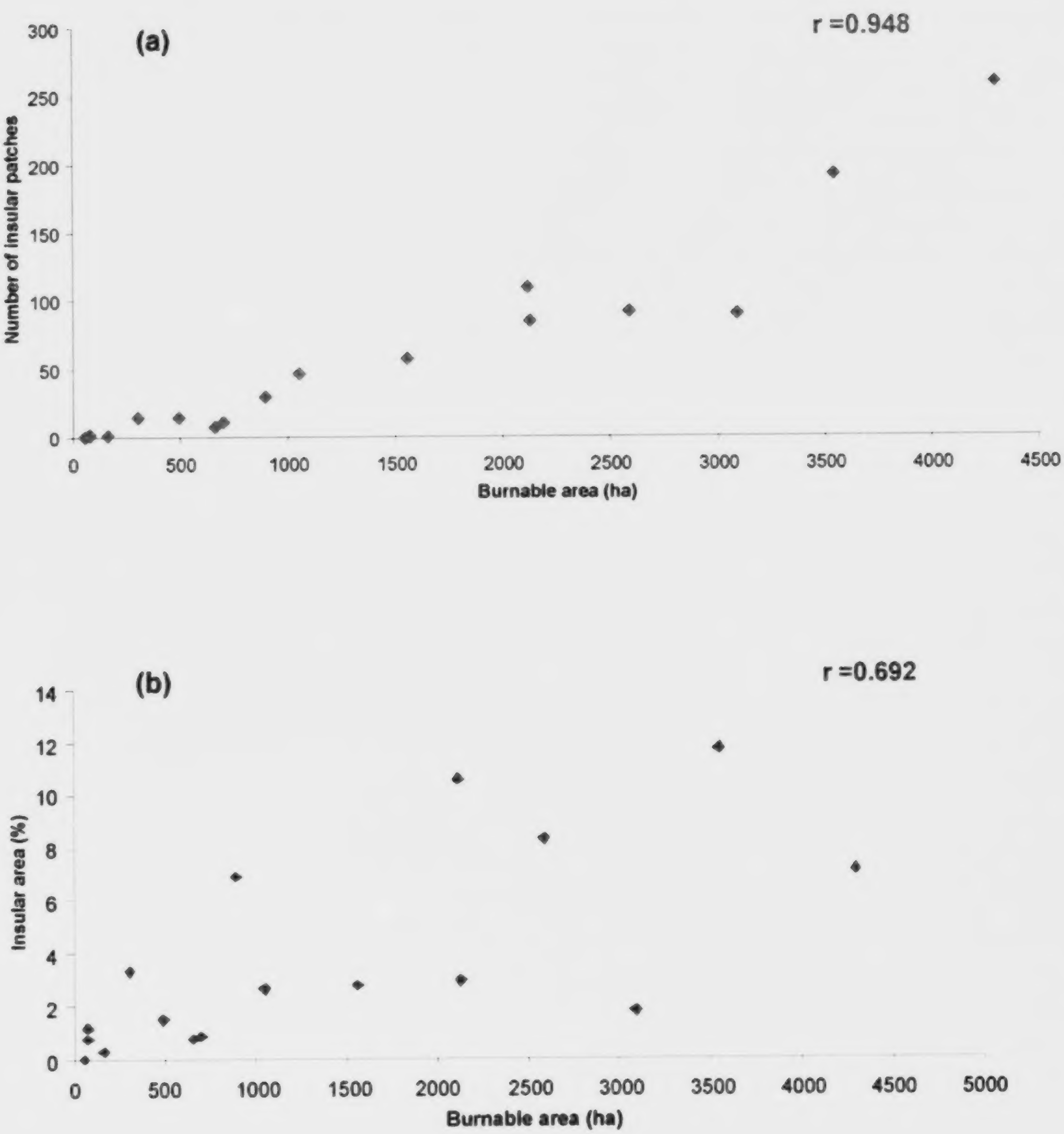


Figure 11. *Insular residual (a) patch number and (b) patch extent (as a percentage of the burnable area) in relation to the burnable area within fire footprints (n=17).*

Peninsular residual patches

OMNR (2001) defines two types of peninsular residual patches, as described in Table 6, both associated with fire footprint perimeters. However, there are some fundamental differences in the nature of their origin. Type 1 patches exist *outside* fire footprints, as a result of the convolutions of perimeters, and were delineated using an OMNR spatial tool (M. Briennesse, OMNR, 2008, pers. com.; Figure 5 in methods). In contrast, Type 2 patches exist *inside* the footprints, and occur within 20 m of the perimeter. These were delineated using the spatial filtering described in Figure 4 in methods. Because of the differences in their derivation, we describe extent and characteristics of Type 1 and Type 2 peninsular residuals separately.

Type 1 Peninsular

Overall, there were 668 Type 1 peninsular patches across the fire footprints. The patches per footprint ranged from 4 (FF-2) to 105 (FF-1) (Table 8). The mean number of patches was 39 ± 8, with 80% coefficient of variation. The extent (total area) of the Type 1 peninsular patches in fire footprints ranged from 9.5 ha (FF-7) to 1648.3 ha (FF-16). The total residual patch area when expressed as a percentage of the fire footprint – not the burnable area within fire footprint as before, because these patches exist *outside* the fire footprints – ranged from 5.8% (FF-7) to 87.0% (FF-4), with a mean of 37.9% ±.6.1, coefficient of variation of 66% and a median of 34.6%.

Number of Type 1 peninsular patches (r= 0.884) within footprints increased with fire footprint size, but their area as a percentage of the footprints decreased, with a weaker correlation coefficient (r= 0.293). Figure 12 illustrates Type 1 peninsular residual patches of fire footprints, using FF-2 and FF-3 as examples.

Table 8. *The extent, number, and variability of Type 1 peninsular patches across the study fire footprints.*

Fire footprint	Residual patch area (%)	Number of patches	Patch size (ha)					
			Maximum	Median	Mean	Standard error	95.0% confidence limit	
							Lower	Upper
FF-1	9.5	105	96.48	0.85	4.12	1.09	1.96	6.27
FF-2	34.7	4	82.61	11.59	26.57	19.01	0.00	87.07
FF-3	67.0	31	426.39	3.39	22.87	13.72	0.00	50.88
FF-4	87.0	24	339.46	1.48	17.86	14.02	0.00	46.86
FF-5	26.4	10	10.32	1.28	2.13	0.97	0.00	4.31
FF-6	14.4	8	2.85	1.36	1.45	0.34	0.64	2.26
FF-7	5.8	12	1.82	0.62	0.80	0.15	0.47	1.12
FF-8	34.6	56	163.57	2.08	13.16	3.52	6.11	20.20
FF-9	47.9	50	142.23	1.92	15.08	4.01	7.02	23.13
FF-10	17.8	31	55.99	7.25	13.14	2.82	7.37	18.90
FF-11	69.1	55	118.78	1.40	8.82	3.23	2.35	15.29
FF-12	17.1	68	74.95	1.49	9.39	2.12	5.15	13.62
FF-13	76.2	20	629.22	1.69	35.85	31.30	0.00	101.36
FF-14	15.0	53	63.16	1.86	8.69	2.02	4.64	12.73
FF-15	30.5	5	12.26	1.47	3.52	2.19	0.00	9.60
FF-16	50.3	104	406.47	1.32	15.85	5.30	5.34	26.36
FF-17	40.9	32	82.65	1.57	9.20	3.51	2.05	16.35

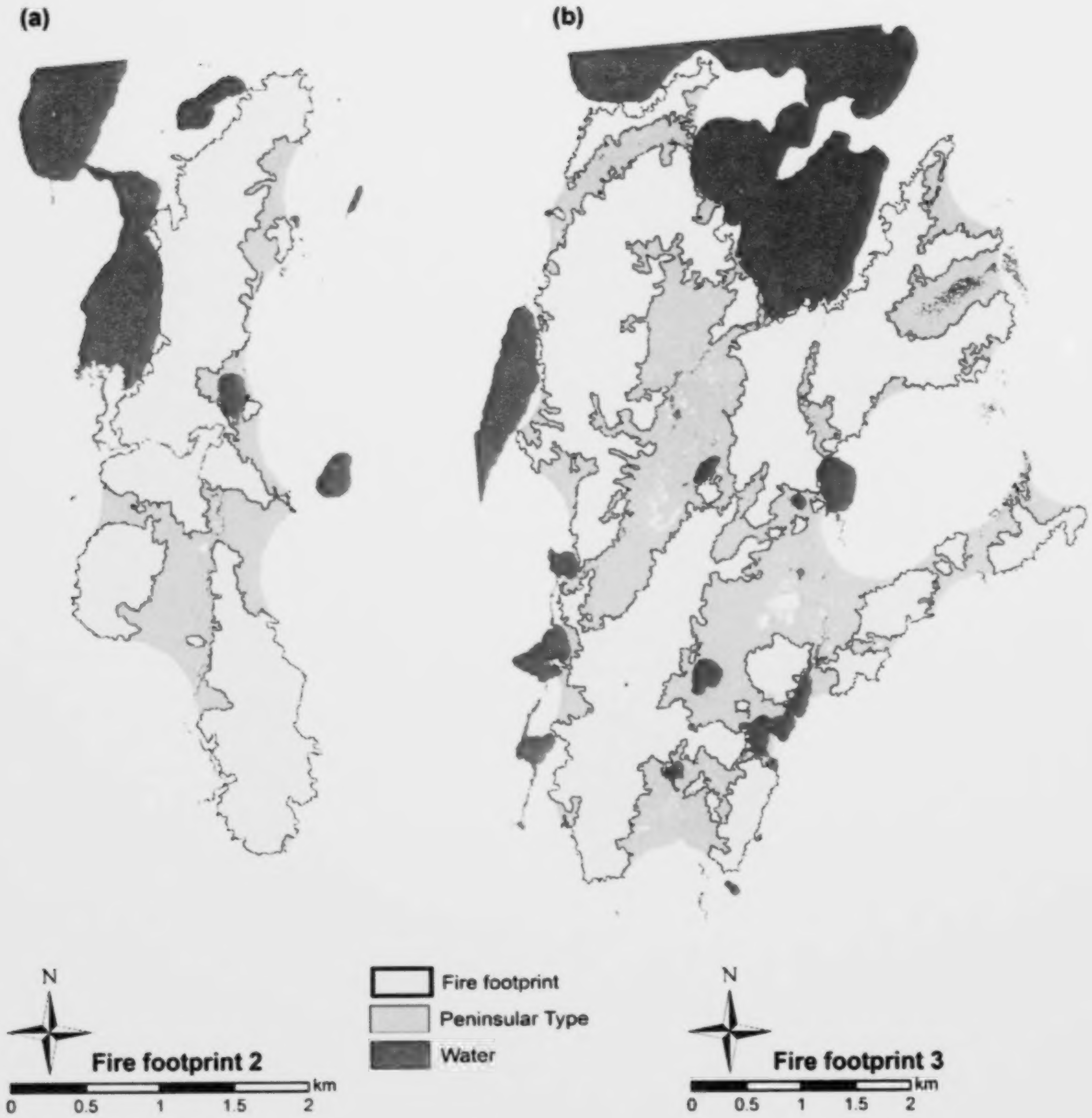


Figure 12. *Peninsular residual patches associated with fire footprints (a) FF2 and (b) FF-3.*

Type 2 Peninsular

Overall, there were 1542 Type 2 peninsular patches across the fire footprints. The patches per footprint ranged from 263 (FF-16) to 2 (FF-15) (Table 9). The mean number of patches was 90 ± 18, with 82% coefficient of variation. The extent (total area) of the Type 2 peninsular patches in fire footprints ranged from of 0.8 ha (FF-15) to 693.9 ha (FF-12). The total residual patch area when expressed as a percentage of the potentially burnable area within fire footprints, because these patches exist *inside* the fire footprints, ranged from 1.5% (FF-15) to 21.5% (FF-11), with a mean of 11.5%±1.2, coefficient of variation of 48% and a median of 11.3%.

Number of Type 2 peninsular patches (r= 0.894) increased with burnable area within fire footprints, but their percentage area (r = 0.200) was not significantly correlated with potentially burnable area. Figure 13 illustrates Type 2 peninsular residual patches in fire footprints, using FF-2 and FF-3 as examples.

Table 9. *The extent, number, and variability of Type 2 peninsular patches across the study fire footprints.*

Fire footprint	Residual patch area (%)	Number of patches	Patch size (ha)					
			Maximum	Median	Mean	Standard Error	95.0% confidence limit	
							Lower	Upper
FF-1	12.0	211	188.34	0.56	2.44	0.91	0.64	4.24
FF-2	7.0	24	3.92	0.65	0.89	0.16	0.56	1.22
FF-3	16.0	118	21.56	0.69	1.43	0.23	0.97	1.89
FF-4	20.2	63	19.87	0.61	1.58	0.40	0.78	2.38
FF-5	11.3	11	1.53	0.76	0.83	0.14	0.52	1.13
FF-6	7.4	9	0.97	0.62	0.66	0.08	0.48	0.85
FF-7	14.7	23	3.28	0.64	1.04	0.19	0.64	1.45
FF-8	6.6	103	20.47	0.45	1.35	0.28	0.80	1.91
FF-9	9.0	98	22.51	0.52	1.43	0.34	0.75	2.11
FF-10	7.6	99	15.19	0.59	1.63	0.26	1.12	2.14
FF-11	21.5	99	23.63	0.49	1.44	0.29	0.86	2.02
FF-12	19.6	185	220.27	0.59	3.75	1.34	1.11	6.39
FF-13	10.6	86	8.18	0.59	1.10	0.15	0.81	1.39
FF-14	12.8	115	100.93	0.51	2.89	1.03	0.85	4.92
FF-15	1.5	2	0.55	0.42	0.42	0.13	0.00	2.05
FF-16	13.2	263	39.23	0.60	1.55	0.21	1.14	1.97
FF-17	4.6	33	4.46	0.45	0.99	0.18	0.62	1.36

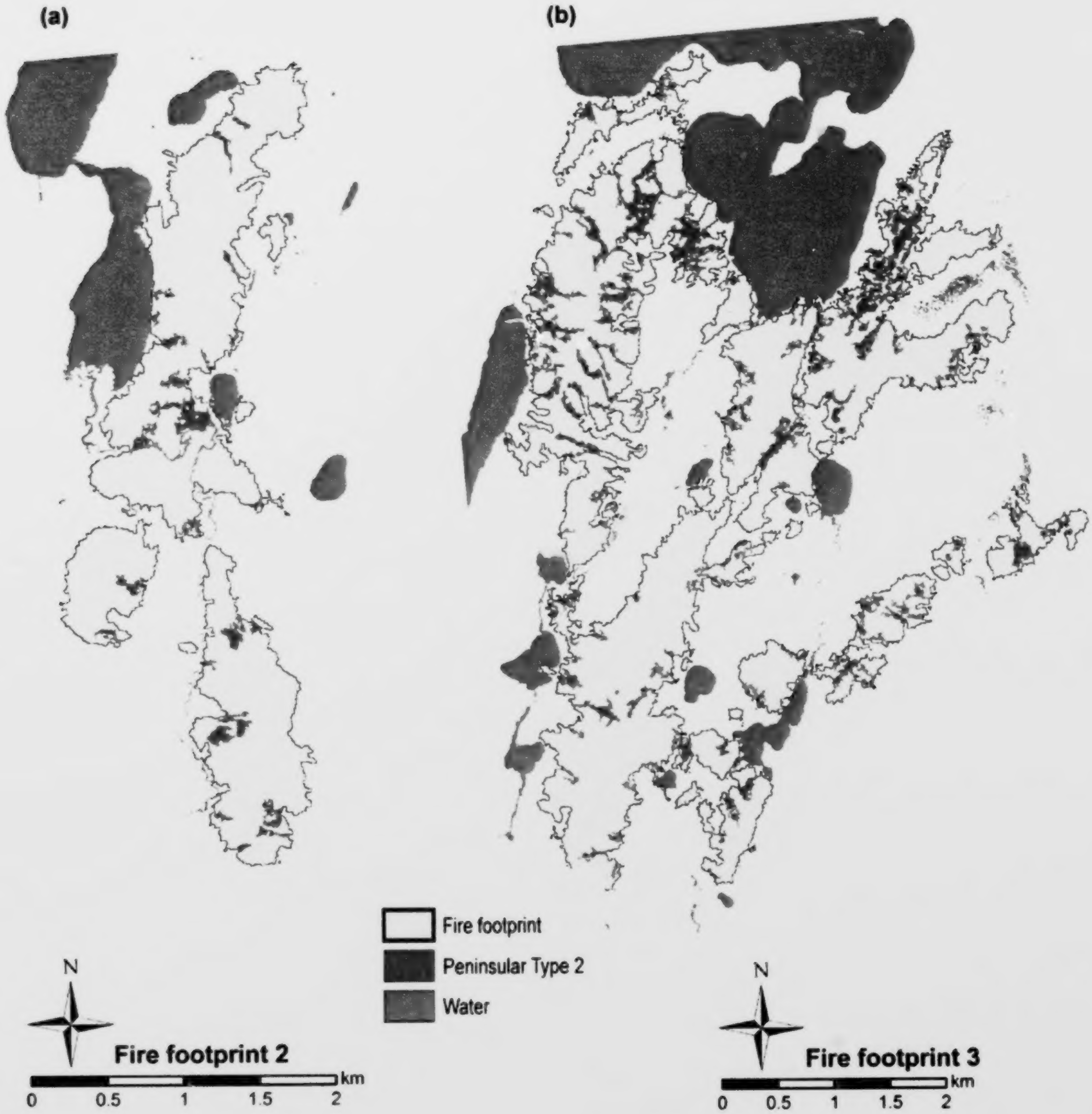


Figure 13. *Type 2 peninsular residual patches within fire footprints (a) FF-2 and (b) FF-3.*

All residuals

Total residual patch extent, expressed as a percentage of the fire footprint area, ranged from 20.7% (FF-7) to 108.7% (FF-4) as detailed in Table 10. The mean residual patch extent among 17 fire footprints was 52.5% ± 5.7%. In all but three fire footprints (FF-1, FF-7, and FF-12), the largest residual component was Type 1 peninsular patches. Insular patches were the smallest residual component in all fire footprints ranging from none (FF-15) to 28.3% (FF-10) of the total residual extent.

Table 10. *Total extent of residual patches (insular, Type 1 peninsular, Type 2 peninsular) as a percentage of the fire footprint area. Here we used the fire footprints as the base because using burnable area within footprints as a base for Type 1 peninsular residuals, which occur outside the footprint, is illogical.*

Fire footprint	Residual patch extent as a percentage of fire footprint area			
	Insular	Peninsular		Total
		Type 1	Type 2	
FF-1	6.8	9.5	11.4	27.7
FF-2	3.3	34.7	7.0	44.9
FF-3	2.6	67.0	16.0	85.6
FF-4	1.5	87.0	20.2	108.7
FF-5	1.2	26.4	11.3	38.8
FF-6	0.8	14.4	7.4	22.5
FF-7	0.3	5.8	14.7	20.7
FF-8	2.9	34.6	6.5	44.1
FF-9	2.8	47.9	8.9	59.5
FF-10	9.8	17.8	7.0	34.7
FF-11	0.7	69.1	20.3	90.2
FF-12	11.1	17.1	18.5	46.7
FF-13	6.6	76.2	10.1	92.9
FF-14	7.0	15.0	10.8	32.8
FF-15	0.0	30.5	1.5	32.0
FF-16	1.7	50.3	12.5	64.5
FF-17	0.8	40.9	4.5	46.3
Mean±SE	3.5±0.8	37.9±6.0	11.1±1.3	52.5±6.5

We remind reader that the fire footprint area was used as the base to express the extent of insular residual patches and Type 2 peninsular residual patches only to provide a common base for all three types of residual patches (because using burnable area within the footprint as a base for Type 1 peninsular residuals is illogical). Using this base decreased the residual patch estimates, by 3.3% on average (but as much as 15.7% in FF-14) due to the presence of unburnable cover types within fire footprints. However, the alternative method of using burnable area within fire footprints as the base for all residual patches is not appropriate given that Type 1 peninsular patches exist entirely outside the fire footprints.

Number of all residual patches (r= 0.969) increased with fire footprints size, but the percentage area of all residuals decreased with increasing fire footprint size with a very weak correlation coefficient (r= 0.141). Thus, as the fire size increases, the number of patches is expected to increase but the relative percentage area in patches is expected to remain the same or decrease.

Details of the extent of all three residual patch types within each of the 17 fire footprints are illustrated in Figures 14-30.

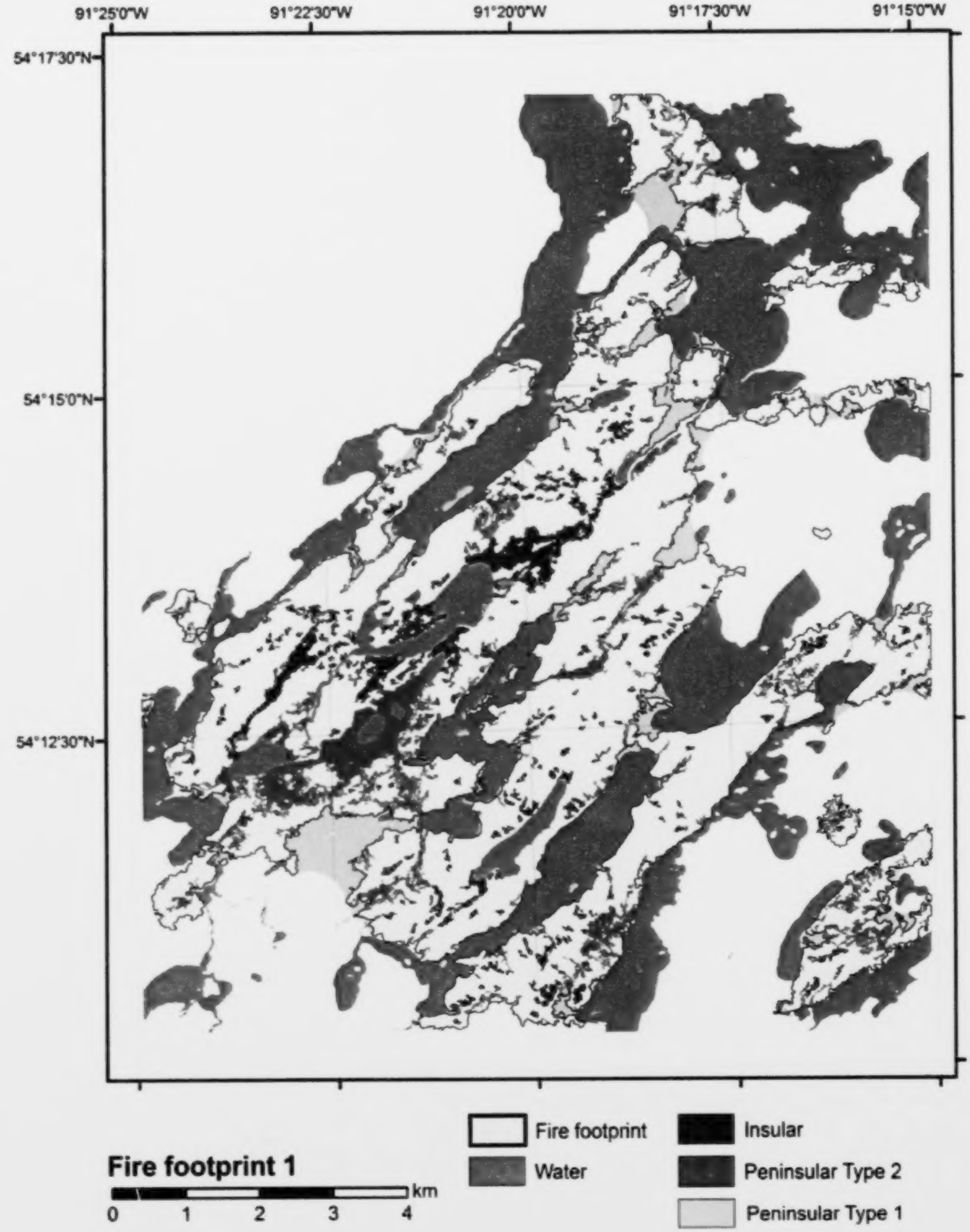


Figure 14. *Fire footprint 1 with its fire perimeter, categories of residual patches, and water bodies. This fire, 4525.3 ha, contained 6.8% insular patches, 9.5% Type 1 peninsular patches, and 11.4% Type 2 peninsular patches as a percentage of the footprint area.*

Figure 15. *Fire footprint 2 with its fire perimeter, categories of residual patches, and water bodies. This fire, 306.7 ha, contained 3.3% insular patches, 34.7% Type 1 peninsular patches, and 7.0% Type 2 peninsular patches as a percentage of the footprint area.*

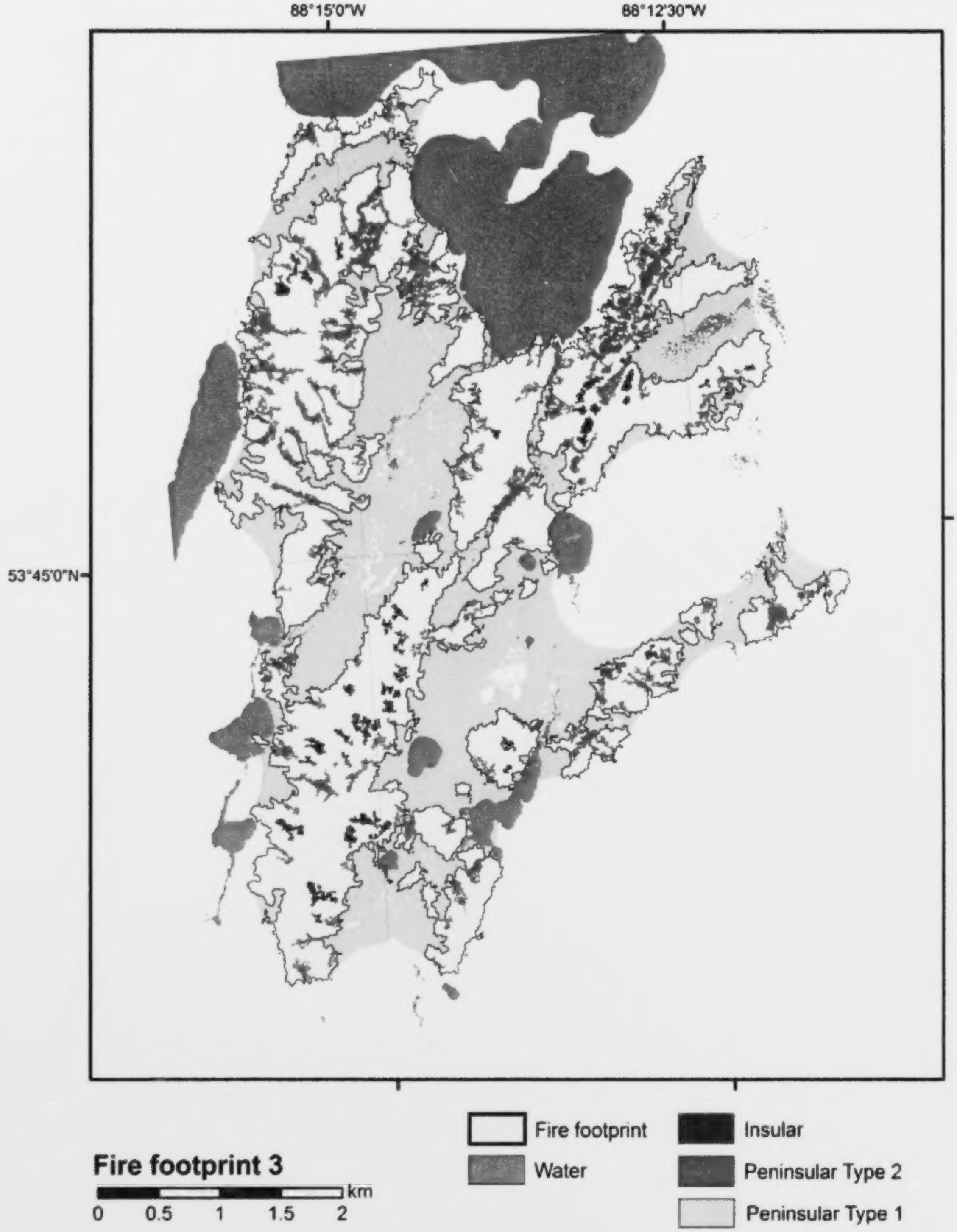


Figure 16. *Fire footprint 3 with its fire perimeter, categories of residual patches, and water bodies. This fire, 1058.0 ha, contained 2.6% insular patches, 67.0% Type 1 peninsular patches, and 16.0% Type 2 peninsular patches as a percentage of the footprint area.*

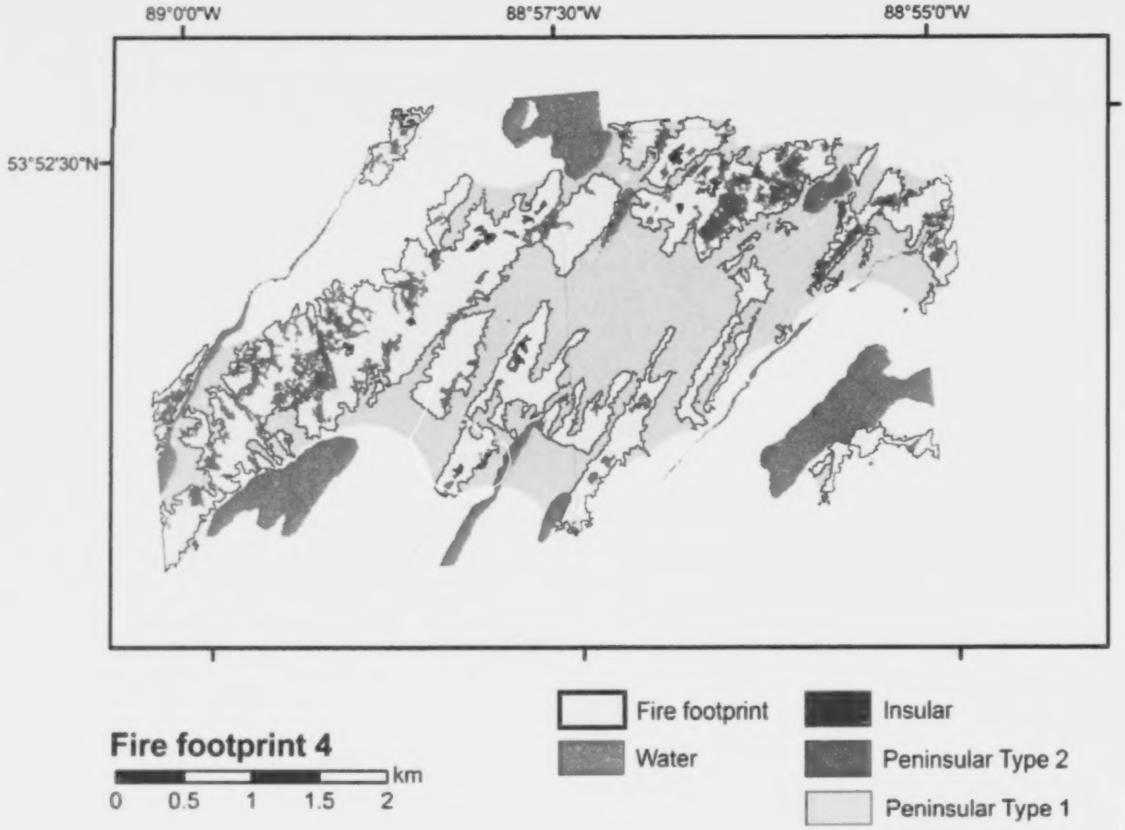


Figure 17. *Fire footprint 4 with its fire perimeter, categories of residual patches, and water bodies. This fire, 492.8 ha, contained 1.5% insular patches, 87.0% Type 1 peninsular patches, and 20.2% Type 2 peninsular patches as a percentage of the footprint area.*

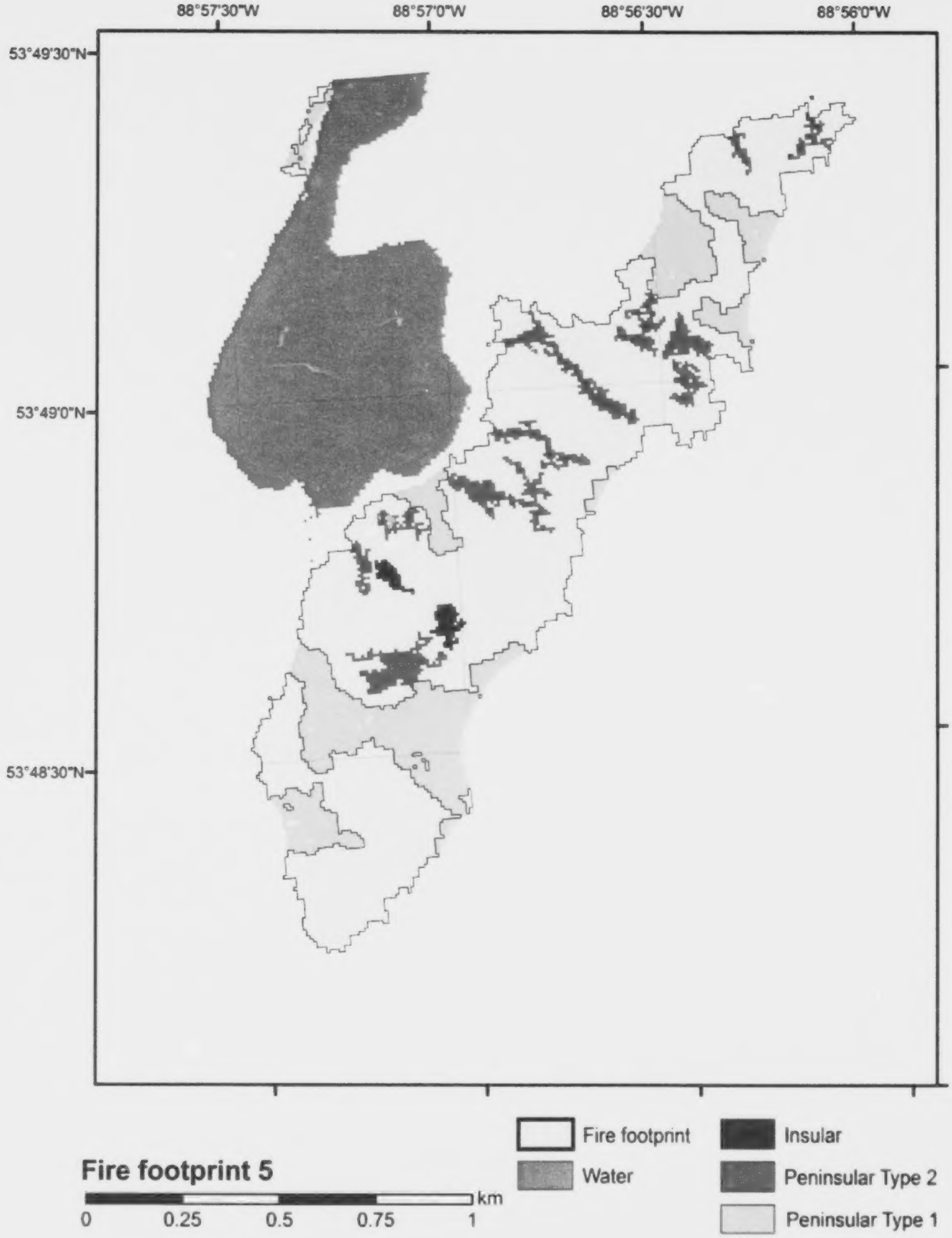


Figure 18. *Fire footprint 5 with its fire perimeter, categories of residual patches, and water bodies. This fire, 80.6 ha, contained 1.2% insular patches, 26.4% Type 1 peninsular patches, and 11.3% Type 2 peninsular patches as a percentage of the footprint area.*

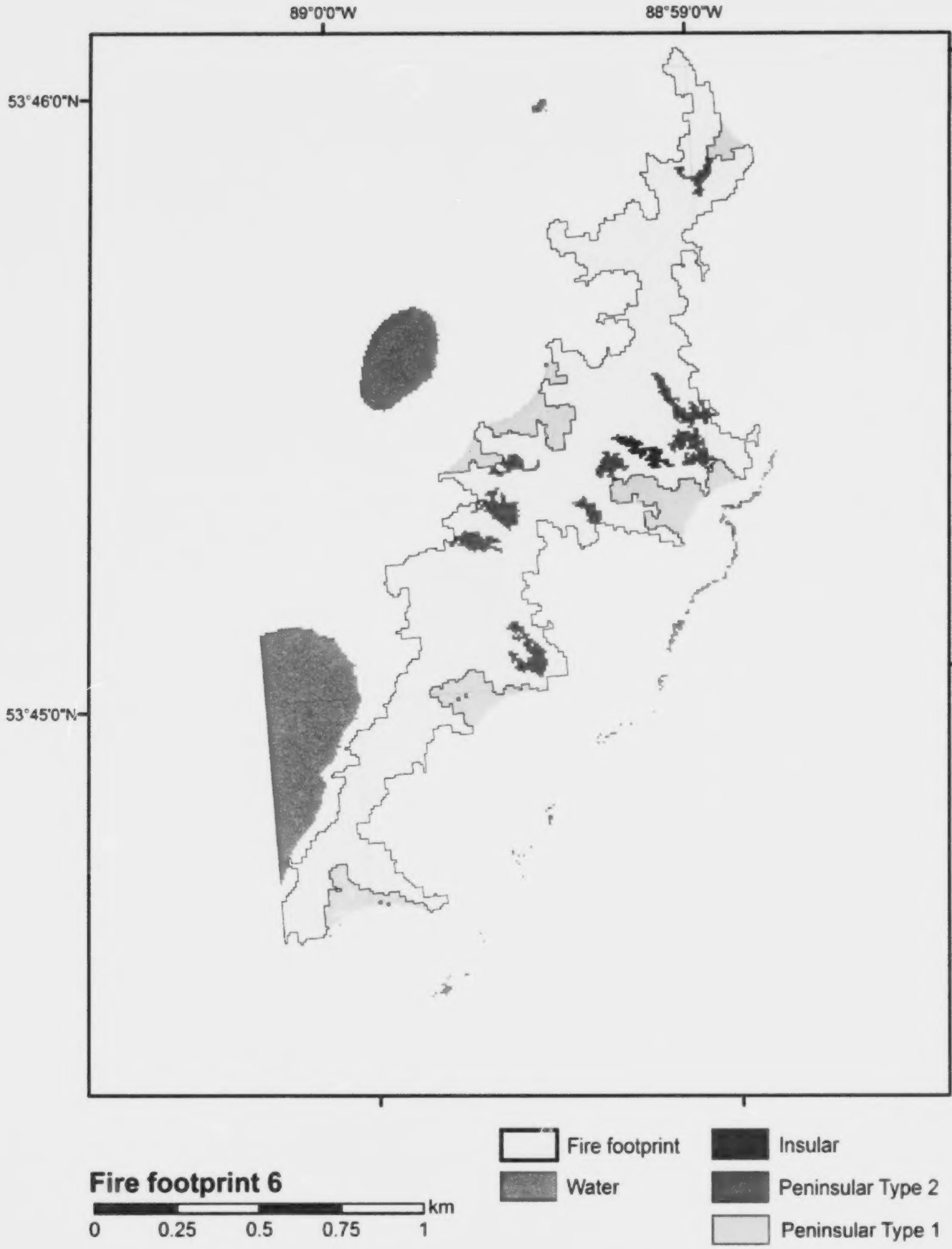


Figure 19. *Fire footprint 6 with its fire perimeter, categories of residual patches, and water bodies. This fire, 80.5 ha, contained 0.8% insular patches, 14.4% Type 1 peninsular patches, and 7.4% Type 2 peninsular patches as a percentage of the footprint area.*

Figure 20. Fire footprint 7 with its fire perimeter, categories of residual patches, and water bodies. This fire, 163.8 ha, contained 0.3% insular patches, 5.8% Type 1 peninsular patches, and 14.7% Type 2 peninsular patches as a percentage of the footprint area.

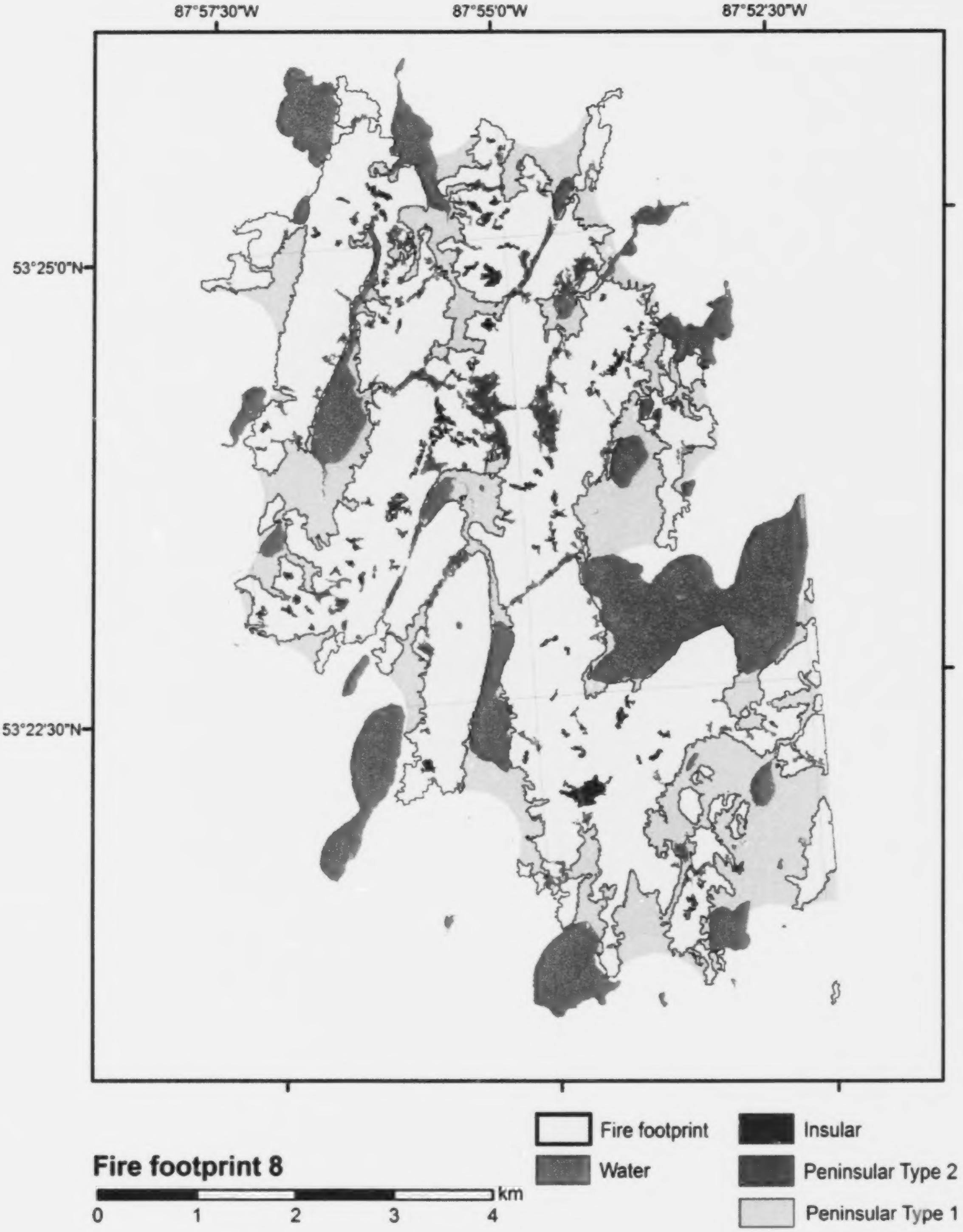


Figure 21. *Fire footprint 8 with its fire perimeter, categories of residual patches, and water bodies. This fire, 2129.1 ha, contained 2.9% insular patches, 34.6% Type 1 peninsular patches, and 6.5% Type 2 peninsular patches as a percentage of the footprint area.*

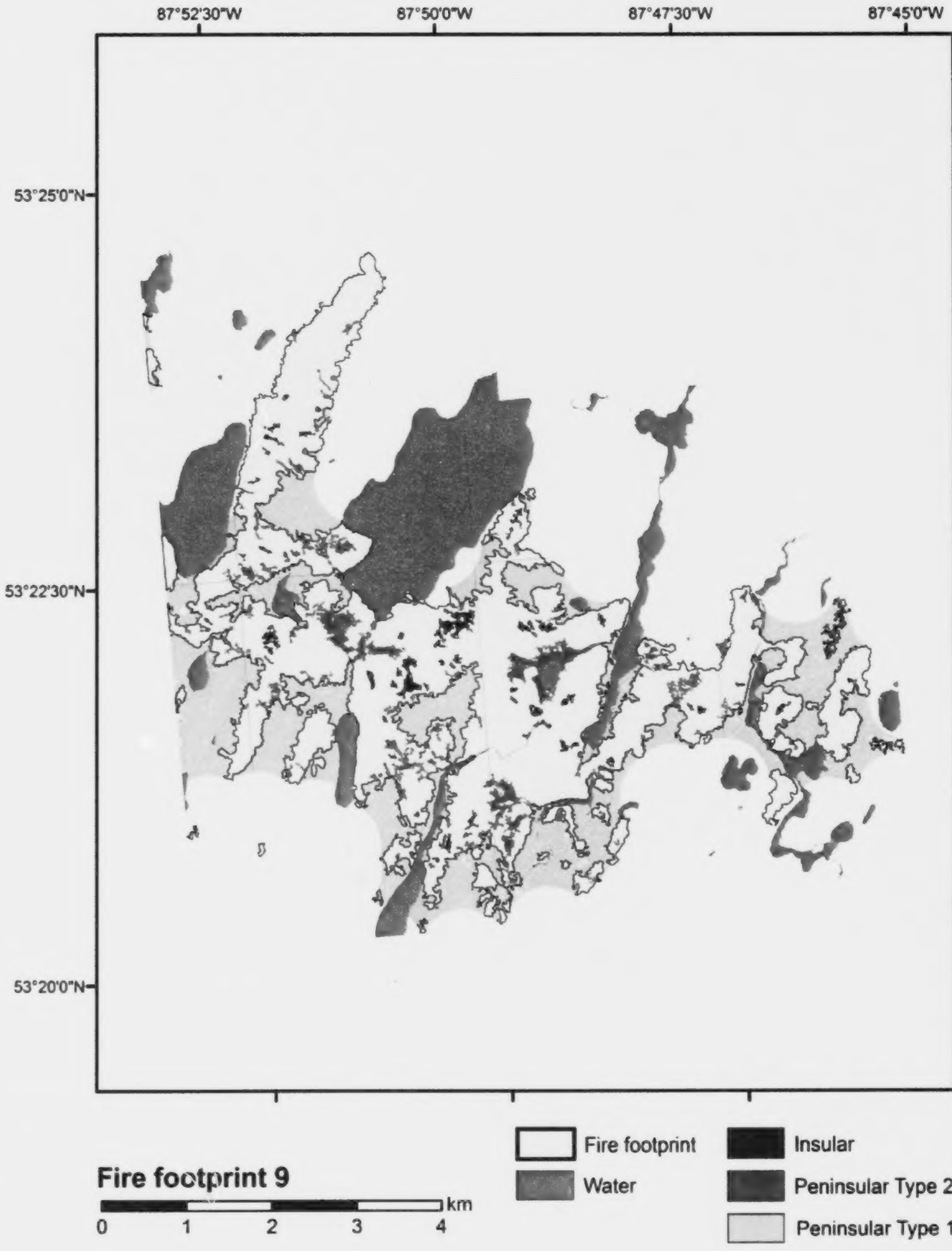


Figure 22. *Fire footprint 9 with its fire perimeter, categories of residual patches, and water bodies. This fire, 1574.9 ha, contained 2.8% insular patches, 47.9% Type 1 peninsular patches, and 8.9% Type 2 peninsular patches as a percentage of the footprint area.*

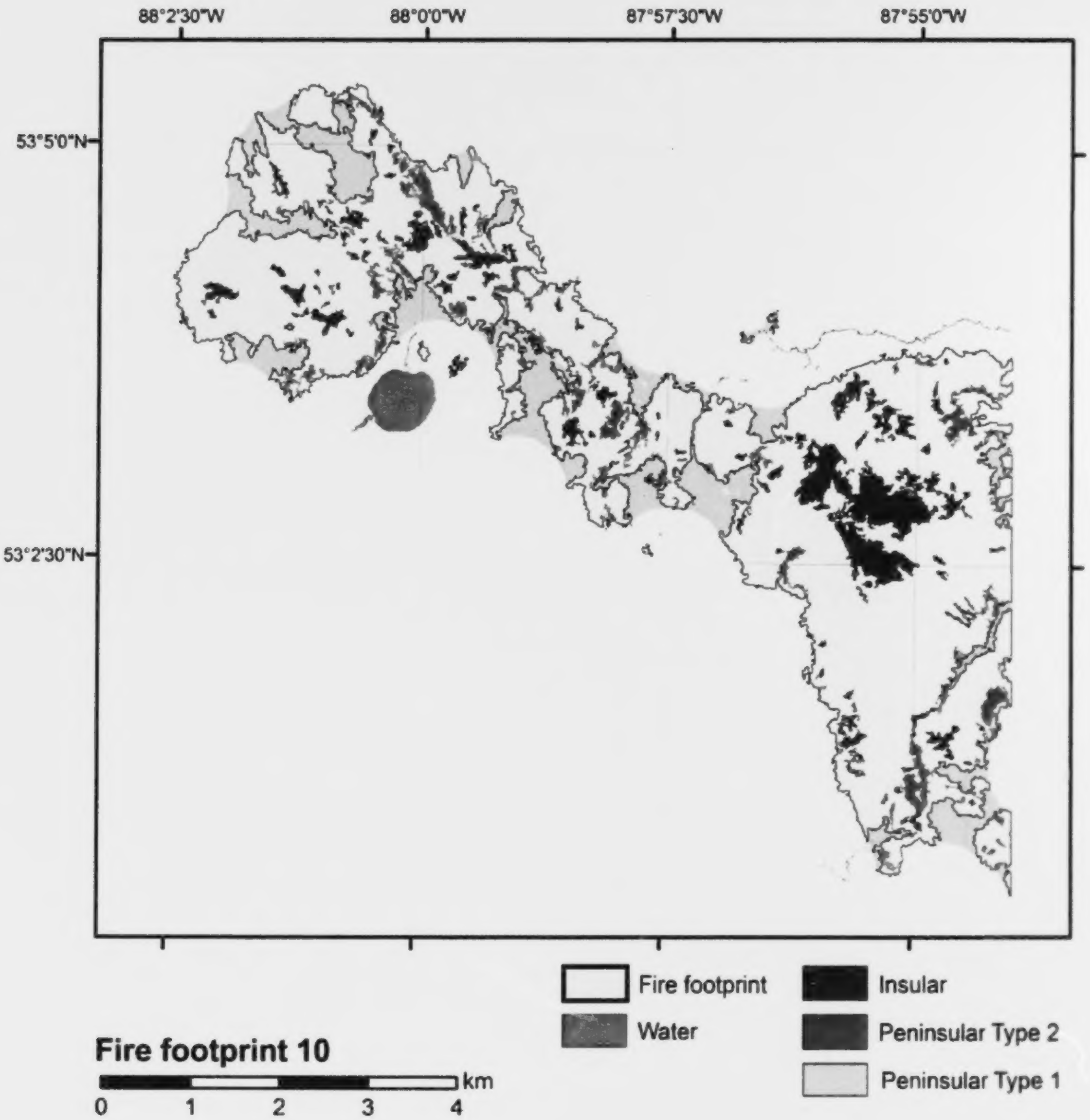


Figure 23. Fire footprint 10 with its fire perimeter, categories of residual patches, and water bodies. This fire, 2286.1 ha, contained 9.8% insular patches, 17.8% Type 1 peninsular patches, and 7.0% Type 2 peninsular patches as a percentage of the footprint area.

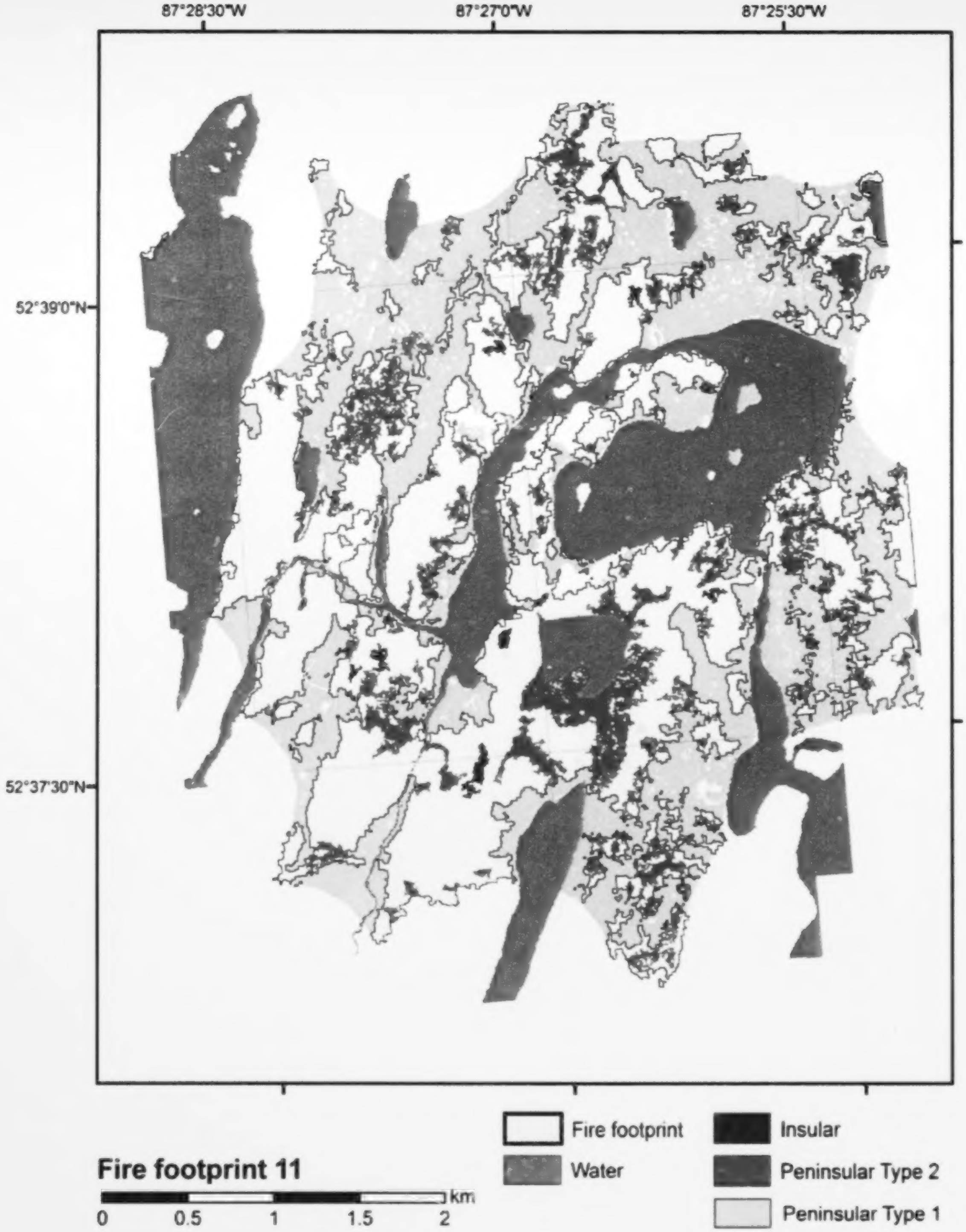


Figure 24. *Fire footprint 11 with its fire perimeter, categories of residual patches, and water bodies. This fire, 701.6 ha, contained 0.7% insular patches, 69.1% Type 1 peninsular patches, and 20.3% Type 2 peninsular patches as a percentage of the footprint area.*

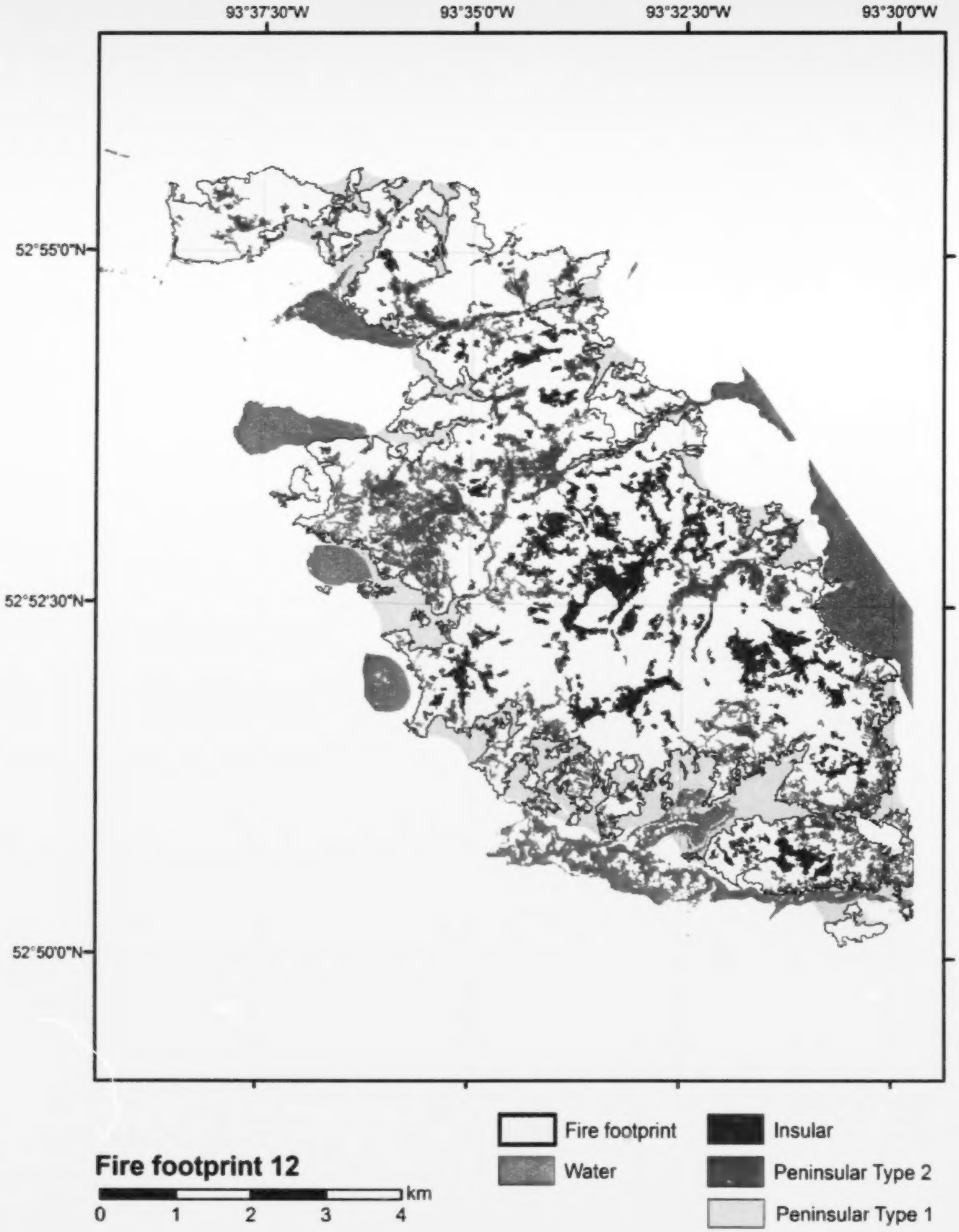


Figure 25. Fire footprint 12 with its fire perimeter, categories of residual patches, and water bodies. This fire, 3741.8 ha, contained 11.1% insular patches, 17.1% Type 1 peninsular patches, and 18.5% Type 2 peninsular patches as a percentage of the footprint area.

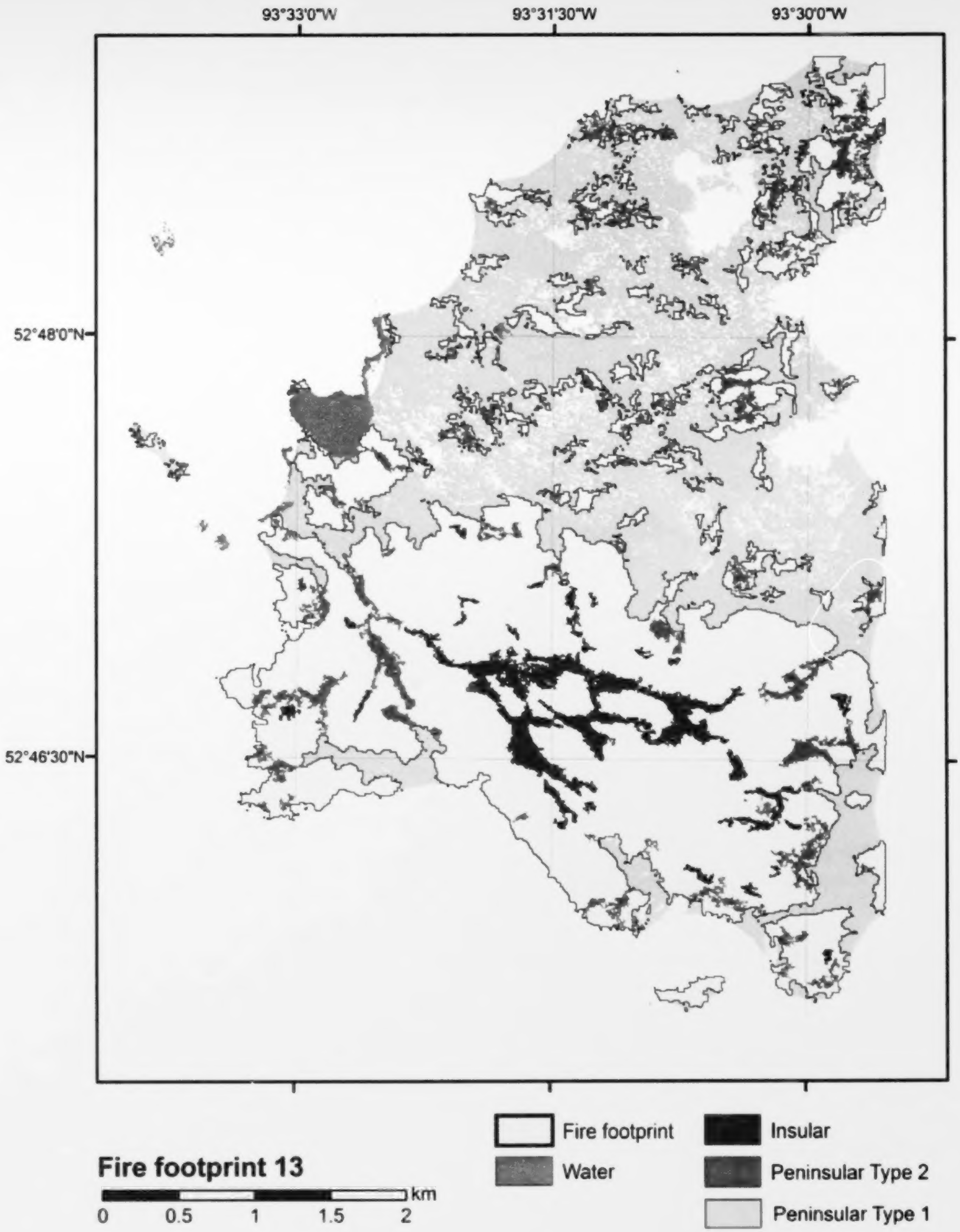


Figure 26. *Fire footprint 13 with its fire perimeter, categories of residual patches, and water bodies. This fire, 940.5 ha, contained 6.6% insular patches, 76.2% Type 1 peninsular patches, and 10.1% Type 2 peninsular patches as a percentage of the footprint area.*

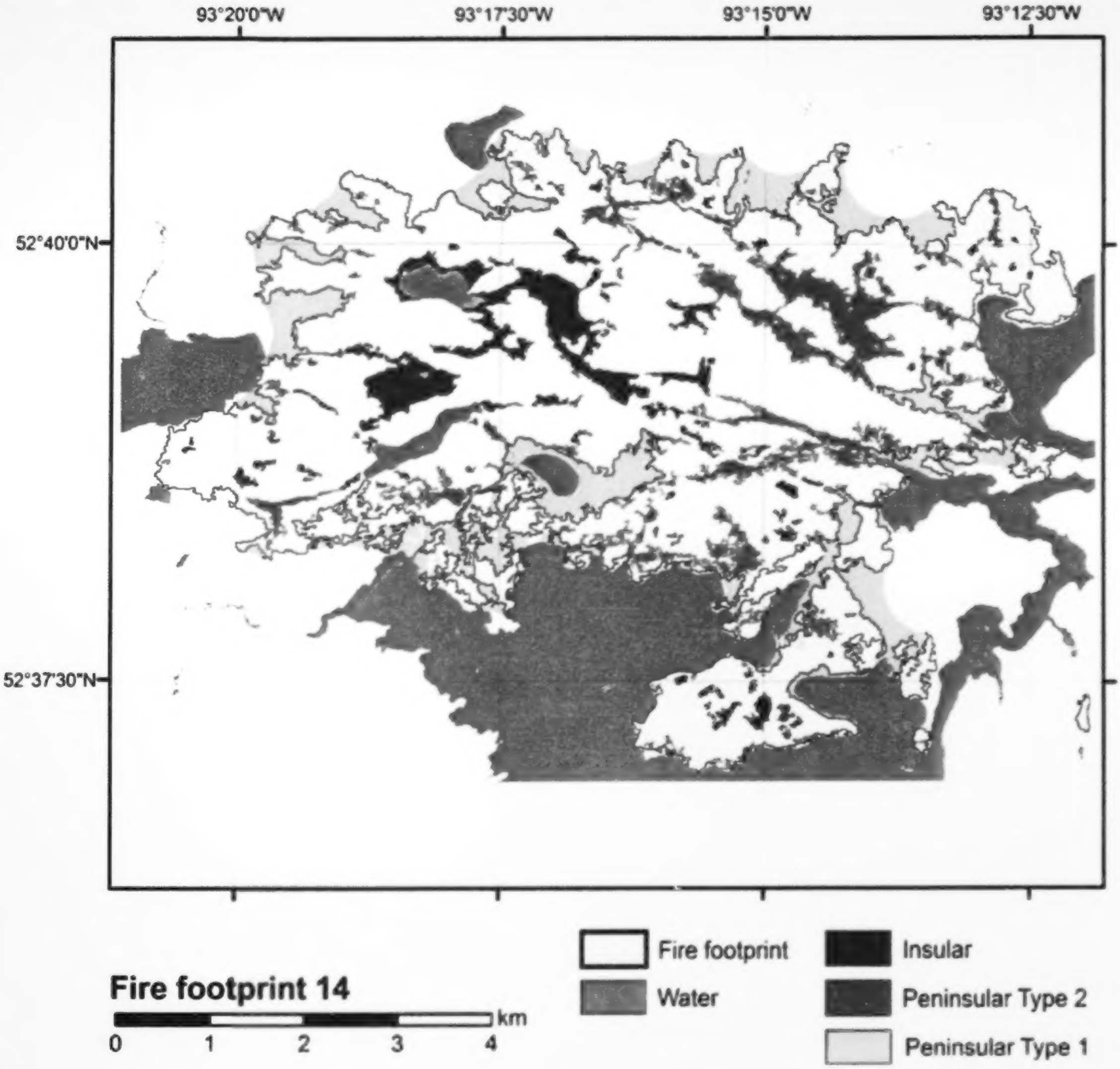


Figure 27. Fire footprint 14 with its fire perimeter, categories of residual patches, and water bodies. This fire, 3072.2 ha, contained 7.0% insular patches, 15.0% Type 1 peninsular patches, and 10.8% Type 2 peninsular patches as a percentage of the footprint area.

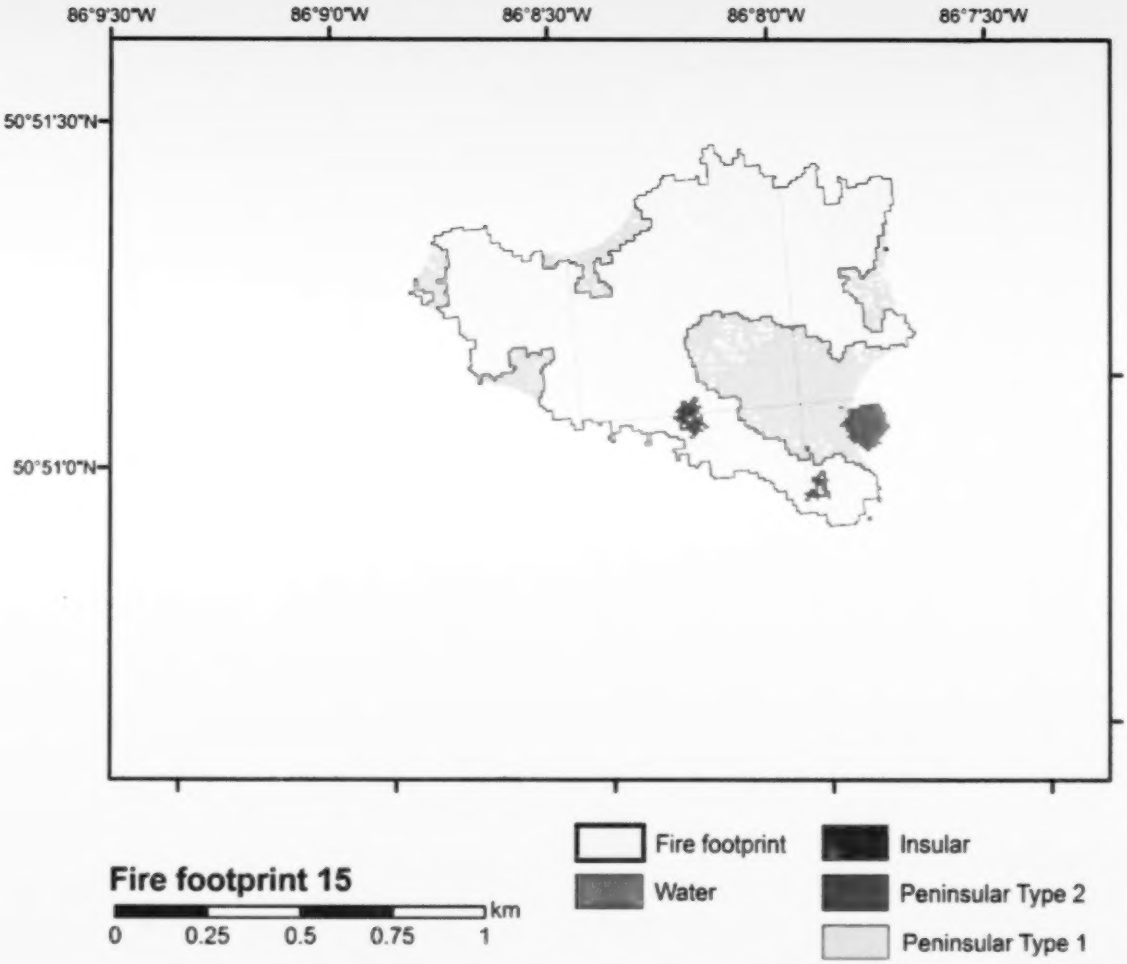


***Figure 28**. Fire footprint 15 with its fire perimeter, categories of residual patches, and water bodies. This fire, 57.7 ha, contained 0% insular patches, 30.5% Type 1 peninsular patches, and 1.5% Type 2 peninsular patches as a percentage of the footprint area.*

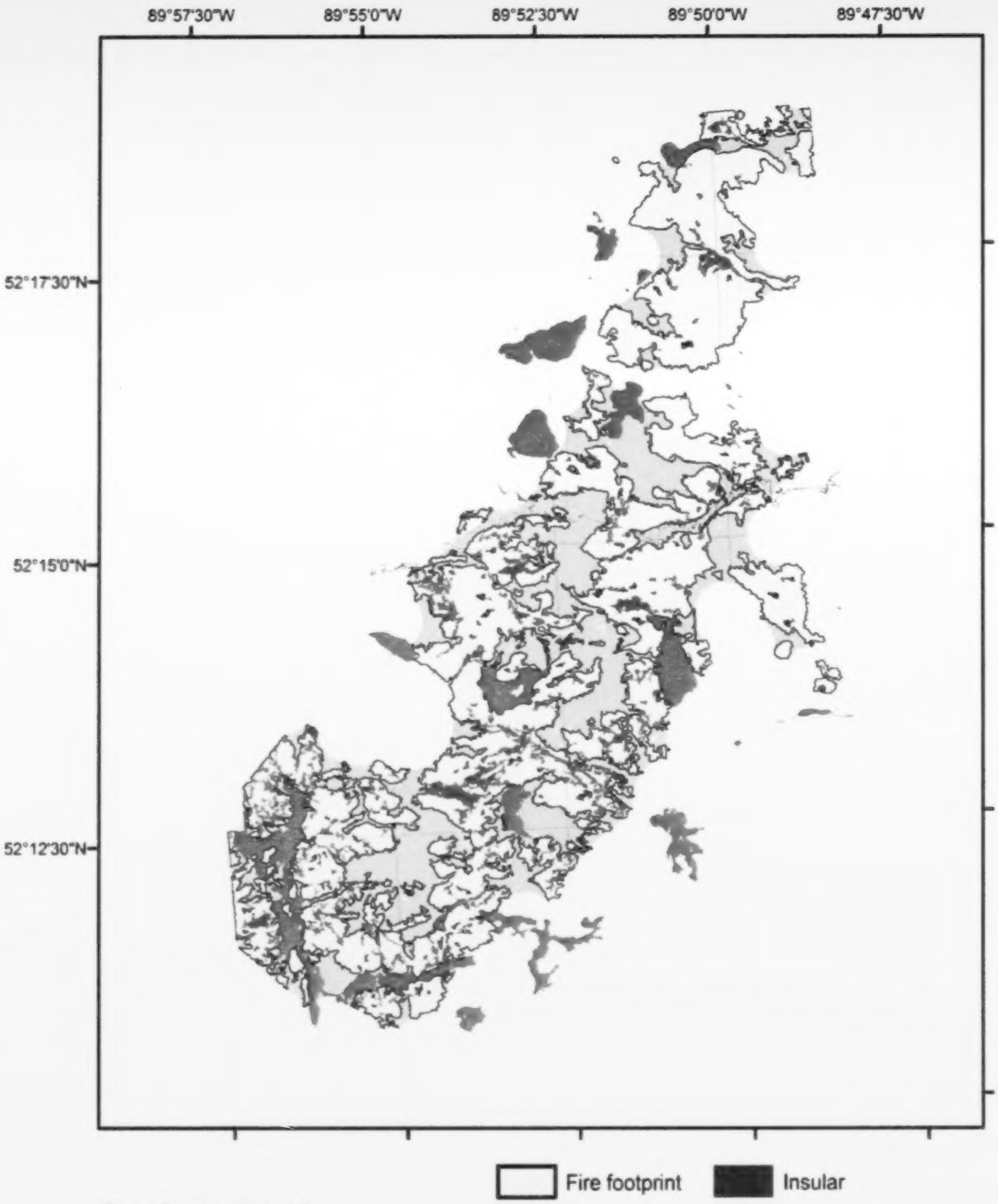


Figure 29. *Fire footprint 16 with its fire perimeter, categories of residual patches, and water bodies. This fire, 3276.9 ha, contained 1.7% insular patches, 50.3% Type 1 peninsular patches, and 12.5% Type 2 peninsular patches as a percentage of the footprint area.*

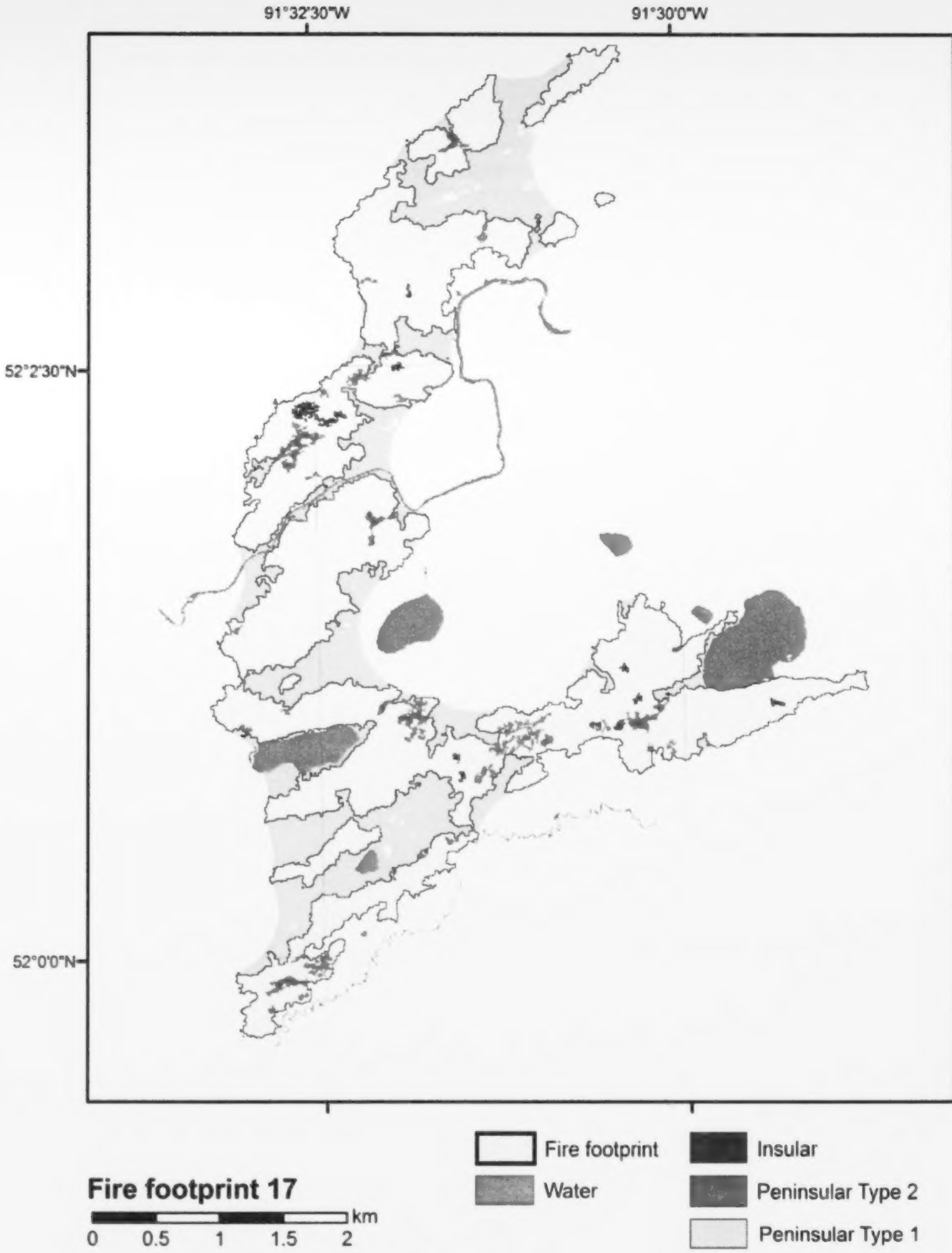


Figure 30. *Fire footprint 17 with its fire perimeter, categories of residual patches, and water bodies. This fire, 719.3 ha, contained 0.8% insular patches, 40.9% Type 1 peninsular patches, and 4.5% Type 2 peninsular patches as a percentage of the footprint area.*

Composition of residual patches

Cover type composition of residual patches within fire footprints was estimated using the classified IKONOS images. As described in the methods, we identified 14 detailed cover classes ranging from recent burns to bedrock. These were merged to nine broader cover type groupings to describe the composition of residual patches (detailed in Table 11). Based on OMNR's definition, water, bedrock, and burn classes are not considered part of residual patches. Therefore, when residual patches encompass burn areas and/or water, those areas were considered inert, and not included in compositional analyses.

Table 11. *Broad cover types within residual patches as derived from their original IKONOS cover type classification.*

Broad cover types	Detailed IKONOS cover types
Burn[1]	Complete burn
	Partial burn
Old burn	Old burn
Conifer	Dense conifer
	Sparse conifer
Deciduous	Deciduous
Shrub	Alder shrub woodland
	Low shrub
Wetland	Treed wetland
	Open wetland
	Marsh
Water[1]	Water
Bedrock[1]	Bedrock and non-vegetated

[1] By definition, burn cover classes, bedrock, and water are not part of residual patches

Insular residuals

Overall composition of insular residual patch area of fire footprints was dominated by conifer (mean=44%), followed by shrub (mean =31%), and wetland cover (mean=23%). Deciduous cover was minimal, comprising <2%. However, the among-fire variability in residual patch composition was high (Figure 31). Conifer cover dominated the insular residual patch area in seven fire footprints; shrub cover in five; and wetland cover in five (Figure 32). Only one fire footprint (FF-12) contained notable extent of deciduous cover.

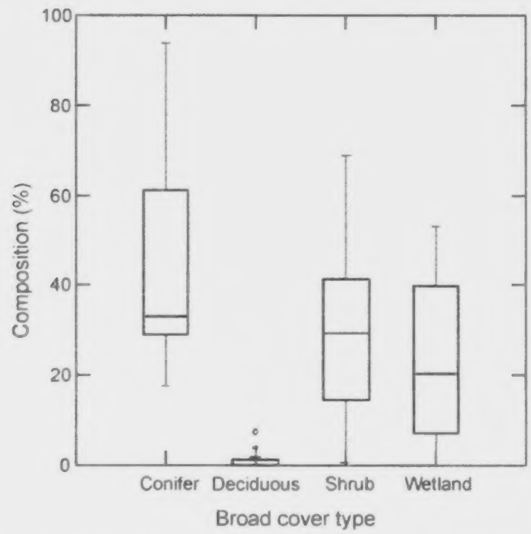


Figure 31. *Among-fire variability in composition of insular residual patches (n = 17 fire footprints). Broad cover types are conifer = dense conifer and sparse conifer; shrub = alder shrub woodland and low shrub; wetland = treed wetland, open wetland, and marsh. Boxes indicate the interquartile range, lines the median, and whiskers the min-max values. Open outliers (*) are 1.5x interquartile range, and the closed outliers (o) are 3x interquartile range.*

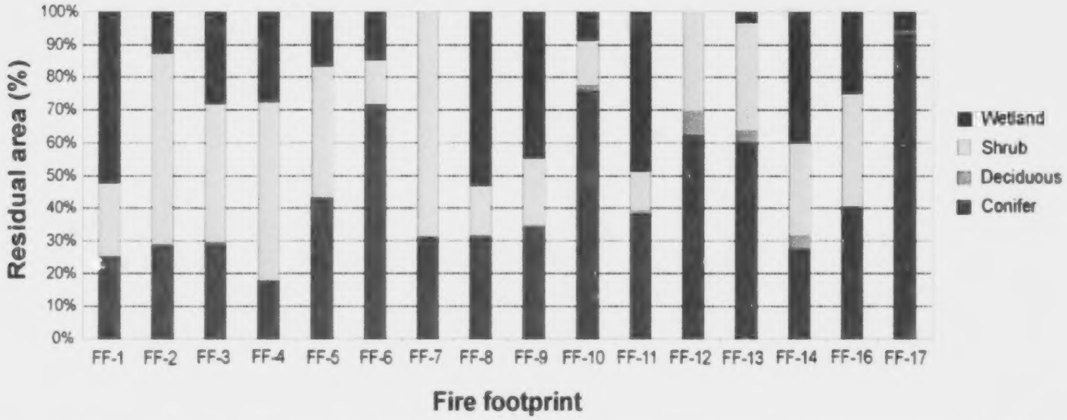


Figure 32. *Relative composition of insular residual patches for the study fire footprints. Broad cover types are conifer = dense conifer and sparse conifer; shrub= alder shrub wood land and low shrub; wetland= treed wetland, open wetland, and marsh.*

Peninsular residuals

Type 1 Peninsular

Overall composition of Type 1 peninsular residual patch area of fire footprints was dominated by conifer (mean=45%), followed by wetland (mean=26%), and shrub cover (mean =22%); deciduous cover was minimal, comprising 3%. However, the among-fire variability in residual patch composition was high (Figure 33). Conifer cover dominated the peninsular residual patch areas in 12 fire footprints; shrub cover in two; and wetland cover in three (Figure 34). Only five fire footprints (FF-10, FF-11, FF-12, FF-13, and FF-14) contained notable extent of deciduous cover in Type 1 peninsular patches.

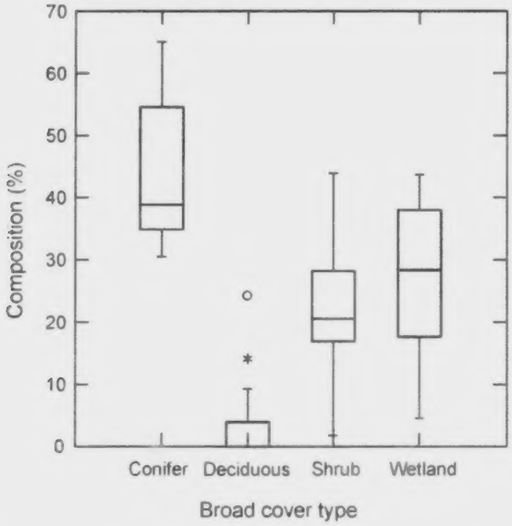


Figure 33. Among-fire variability in composition of Type 1 peninsular residual patches (n= 17 fire footprints). Broad cover types are conifer = dense conifer and sparse conifer; shrub= alder shrub woodland and low shrub; wetland= treed wetland, open wetland, and marsh. Boxes indicate the interquartile range, lines the median, and whiskers the min-max values. Open outliers (*) are 1.5x interquartile range, and the closed outliers (o) are 3x interquartile range.

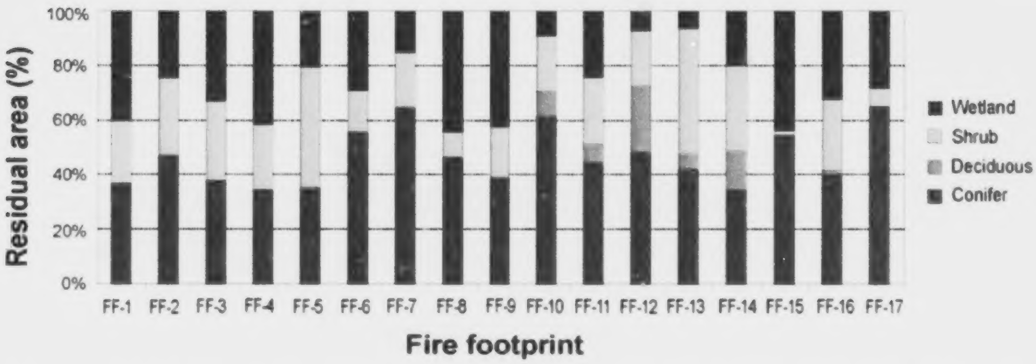


Figure 34. Relative composition of Type 1 peninsular residual patches for the study fire footprints. Broad cover types are conifer = dense conifer and sparse conifer; shrub= alder shrub wood land and low shrub; wetland= treed wetland, open wetland, and marsh.

Type 2 Peninsular

Overall composition of Type 2 peninsular residual patch area of fire footprints was dominated by conifer (mean=37%), followed by shrub (mean =34%), and wetland cover (mean=22%). Deciduous cover was minimal, comprising <2% .However, the among-fire variability was high in residual patch composition (Figure 35). Conifer cover dominated the Type 2 peninsular residual patch area in seven fire footprints; shrub cover in four; and wetland cover in five (Figure 36). Only three fire footprints (FF-12, FF-13, and FF-14) contained notable extent of deciduous cover in Type 2 peninsular patches.

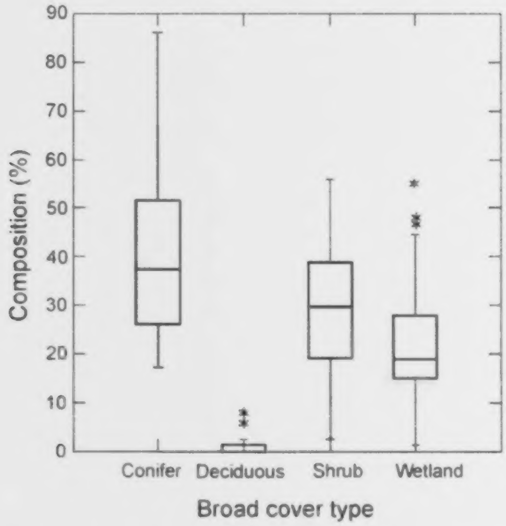


__Figure 35.__ Among-fire variability in composition of Type 2 peninsular residual patches (n= 17 fire footprints). Broad cover types are conifer = dense conifer and sparse conifer; shrub= alder shrub woodland and low shrub; wetland= treed wetland, open wetland, and marsh. Boxes indicate the interquartile range, lines the median, and whiskers the min-max values. Open outliers (*) are 1.5x interquartile range, and the closed outliers (o) are 3x interquartile range.

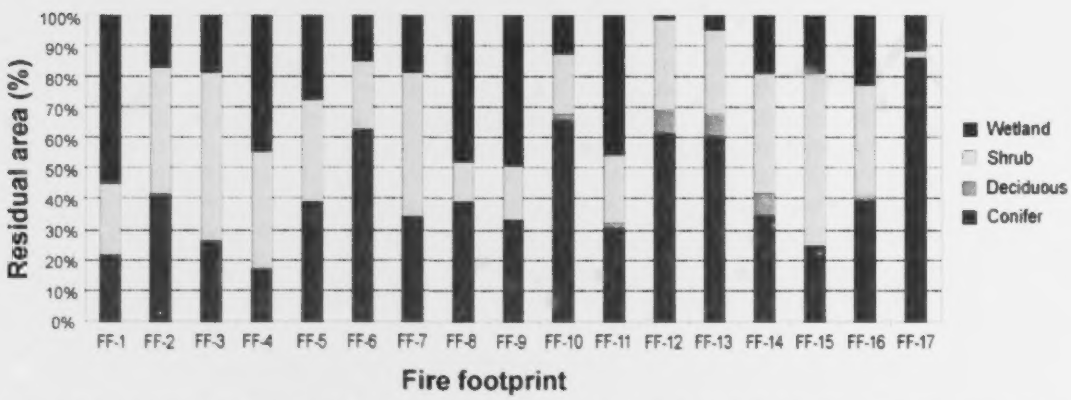


__Figure 36.__ Relative composition of Type 2 peninsular residual patches for the study fire footprints. Broad cover types are conifer = dense conifer and sparse conifer; shrub= alder shrub wood land and low shrub; wetland= treed wetland, open wetland, and marsh.

Spatial characteristics of residual patches

Insular residuals

Spatial distribution within fire footprints

We examined two aspects of spatial distribution of insular residual patches. First, we examined the spatial autocorrelation of insular patches within each fire footprint. As shown in Figure 37, Moran's I values (Moran 1948) were very low, ranging from 0.018 to -0.312, and statistically not significant ($p \geq 0.1$). This indicates that there was no significant spatial autocorrelation among insular patches within fire footprints, and their occurrence within fire footprints was independent of one another.

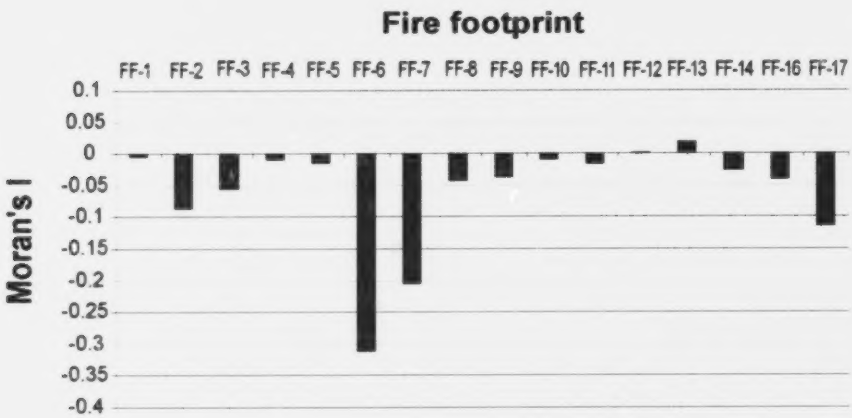


Figure 37. Moran's I values for insular residual patches in the study fire footprints. This indicates that in all fires insular residuals are autocorrelated very weakly.

Second, we examined the occurrence of insular patches in relation to the geometry of the fire footprint. Two approaches were used: (a) determining the nearest Euclidean distance from the footprint perimeter to insular patches, and (b) determining the insular patch area in a concentric series of 100-m-wide internal buffers within each footprint.

The nearest distance measure indicated that most insular patches, across all fire footprints, are proximal to the fire perimeter (Figure 38a), with almost 40% of all patches occurring within 100 m of the perimeter. Even in the large fire footprints, the nearest distances were low (Figure 38b). However, this presents an incomplete view of their distribution within fire footprints because patches, even though their edges are proximal to fire perimeters, can extend inwards depending on their size and the overall size of the fire footprint.

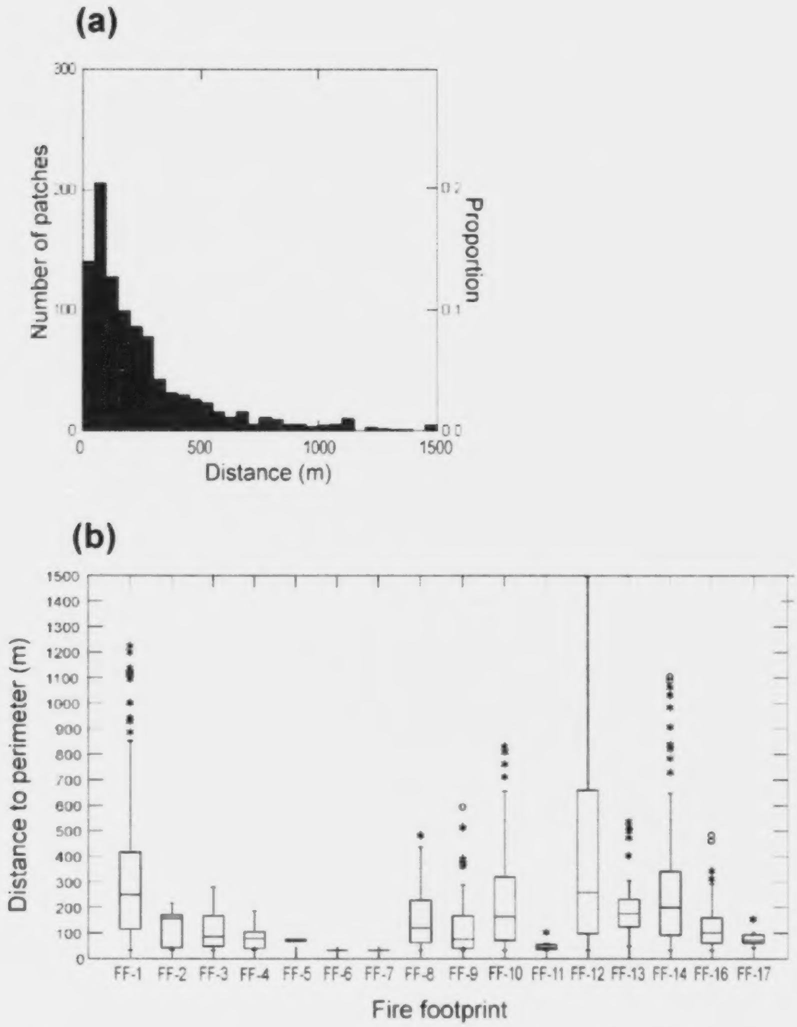


Figure 38. *Proximity of insular patches to their fire perimeters (a) frequency distribution of nearest distance of residual patches to fire perimeter across all fire footprints, and (b) among-fire variability in patch distance to fire perimeter. Boxes indicate the interquartile range, lines the median, and whiskers the min-max values. Open outliers (*) are 1.5x interquartile range, and the closed outliers (o) are 3x interquartile range.*

In the second approach, a series of concentric buffers were imposed starting from the perimeter and extending inwards, continuing until the area of the bands was 0. The number of buffers varied with the size of the fire footprint, from 2 buffers in small (FF-5, FF-6, FF-15) to 14 in large (FF-1, FF-14), and a maximum of 19 (FF-12). The area within each 100-m-wide buffer, as a fraction of the total footprint area decreased rapidly with increasing distance from the perimeter in smaller footprints (Figure 39), and gradually in larger footprints. Then, we examined the insular residual patch extent and number within each 100 m-wide buffer area.

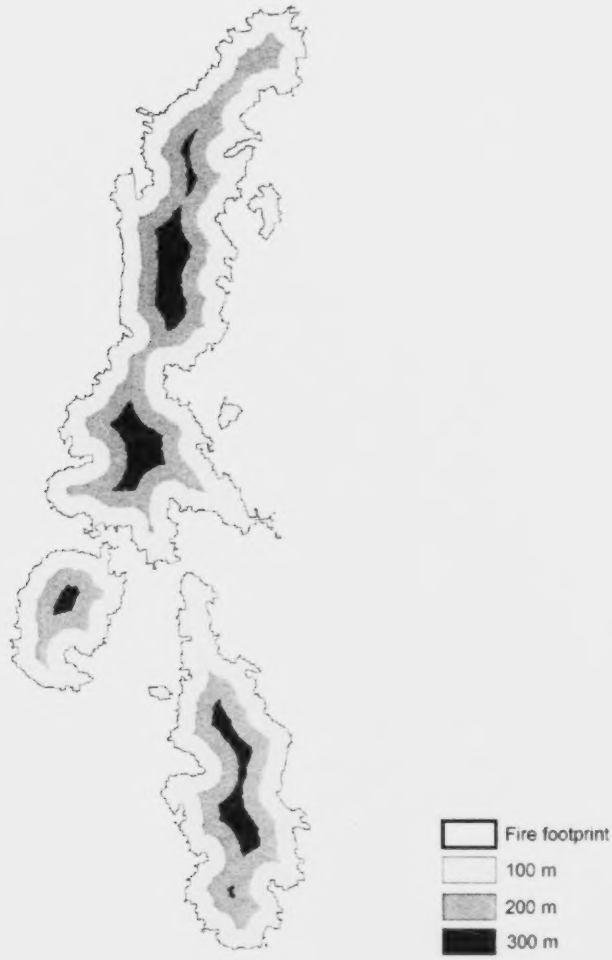


Figure 39. *Schematic of concentric 100 m-wide internal buffers within a fire footprint (FF-2) showing the decrease in relative area towards the centre.*

Overall, the insular residual patch extent within buffer areas, expressed as a percentage of the buffer area, increased from 100 m to 200 m except in FF-7 (Table 12). In many fire footprints (e.g., FF-2, FF-10, FF-12, and FF-13) this increase was continuous towards interior. As well, some footprints, such as FF-10, FF-12, FF-13, and FF-14, contained high percentages of insular residual extent in their interior, much higher than the relative overall insular percentage of those footprints.

Table 12. *Insular residual patch extent as a percentage of the 100 m-wide internal buffers (insular area/buffer area *100) within study fire footprints. Note: Fire footprints are ordered from smallest (FF-6) to largest (FF-1); FF-15 is not shown because it did not contain insular residuals. Shaded cells indicate no buffer areas within footprints at those distances.*

Distance from perimeter (m)	Insular residual patch extent (%) in fire footprints															
	FF-6	FF-5	FF-7	FF-2	FF-4	FF-11	FF-17	FF-13	FF-3	FF-9	FF-8	FF-10	FF-14	FF-16	FF-12	FF-1
100	0.6	0.3	0.3	1.1	1.0	0.3	0.3	0.2	0.8	1.0	0.8	1.2	0.6	0.5	1.1	0.9
200	1.8	4.6	0.0	4.6	3.2	2.0	2.2	2.9	4.9	4.1	3.8	6.0	3.5	3.0	6.4	4.3
300			0.0	14.1	2.8	1.4	0.6	6.6	7.1	5.8	5.3	10.2	4.4	3.7	9.7	5.4
400					0.0	0.0	0.0	9.5	7.5	4.9	4.9	10.7	6.1	4.4	15.2	8.0
500						0.0		18.0		3.1	6.3	10.0	9.4	2.1	15.2	12.4
600								17.7		3.1	5.2	14.8	8.9	4.4	13.4	16.8
700								29.1		7.9	0.0	17.4	7.5	0.0	17.2	17.7
800								34.9				27.3	10.7		17.2	26.0
900												31.5	18.6		20.7	19.9
1000												33.7	23.6		20.2	16.3
1100												49.5	24.6		22.2	16.9
1200												72.6	18.1		25.2	9.7
1300												95.2	16.9		22.5	5.6
1400													0.0		24.1	1.1
1500															35.2	
1600															39.0	
1700															42.9	
1800															36.5	
1900															26.6	
Footprint insular %	**0.8**	**1.2**	**0.3**	**3.3**	**1.5**	**0.7**	**0.8**	**6.6**	**2.6**	**2.8**	**2.9**	**9.8**	**7.0**	**1.7**	**11.1**	**6.8**

However, this does not necessarily indicate a bias of insular residual patch occurrence towards the interior. The inflation of residual patch area percentages could result from the progressive decrease in area towards the interior of the fire footprint. To alleviate this confounding, we assessed insular residual patch extent at varying distances in comparison to the relative area within fire footprints as an area fraction ratio. The insular area fraction for each buffer is the insular area within that buffer/insular area within the footprint, and the buffer area fraction is area of that buffer/footprint area. This weighted ratio indicates whether the insular extent in each buffer is proportionate throughout the fire footprint. If the spatial distribution of insular residual patch area within footprints is uniform (probability of occurrence of residual patch area is equal among all distance classes through the footprint), then the expected ratio of insular fraction: buffer area fraction is 1 for each distance category.

Figure 40 shows the variability of insular fraction:buffer area fraction ratio among fire footprints at different distances from their perimeters. It appears that even by taking in to account the area of the buffers and the total insular extent of footprints, the interior of fire footprints contained relatively higher proportion of residual patch extent than expected. The insular residual patch extent was lowest (relative to what was expected) near the perimeters in all fire footprints. However, it is difficult to generalize any overall trends of increasing insular residual patch extent towards interior given the high variability among fire footprints in size, shape, and overall residual extent.

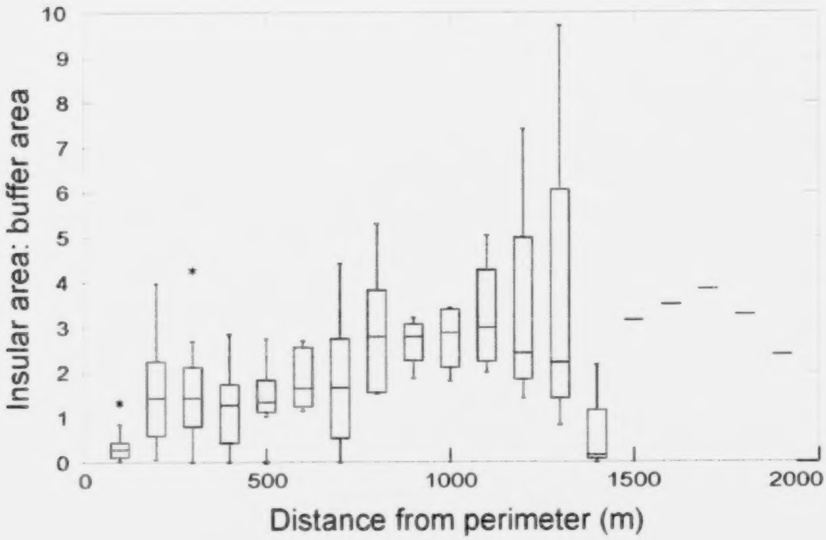


Figure 40. *Variability in the proportionate insular residual patch extent in internal 100 m-wide buffers with increasing distance from fire footprint perimeters. Insular area fraction:buffer area fraction = (insular extent in buffer/total insular extent in footprint)/(buffer area/footprint area). Only fire footprint FF-12 had buffer area beyond 1400 m. Boxes indicate the interquartile range, lines the median, and whiskers the min-max values. Open outliers (*) are 1.5x interquartile range, and the closed outliers (o) are 3x interquartile range.*

Figure 41 illustrates the insular area fractions and buffer area fractions at varying distances in all fire footprints. Area fraction ratio can be visually interpreted thus: (a) when buffer area fraction (white bars) is less than insular area fraction (black bars) the area fraction is >1 and more insular residual patch extent than expected occurs at that distance; (b) when buffer area fraction (white bars) is higher than insular area fraction (black bars), the area fraction ratio is <1 and less insular residual patch extent than expected occurs at that distance; and (c) when buffer area fraction (white bars) equals insular area fraction (black bars), the area fraction ratio is 1 and the insular residual patch extent at that distance is what would be expected. In the study sample, all fire footprints except FF-7 had area fractions <1 at 100 m.

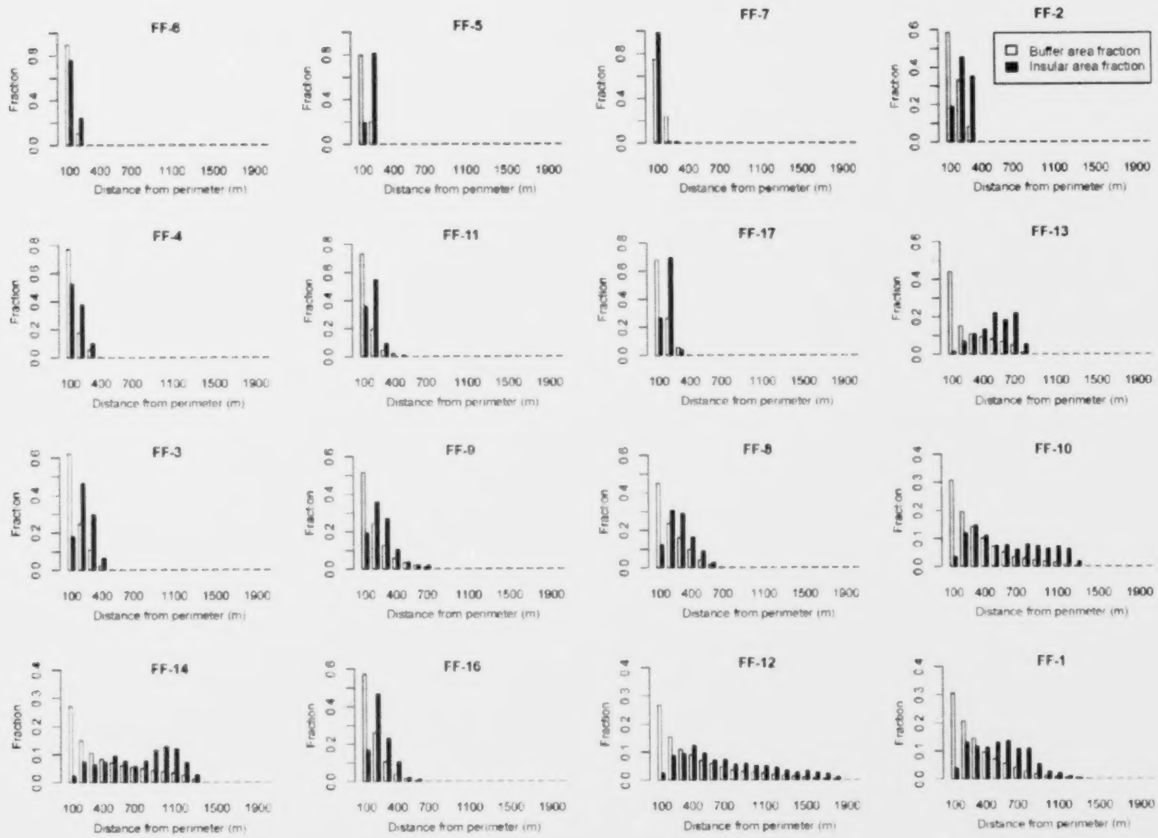


Figure 41. Area fractions at varying distances within study fire footprints. Note: Fire footprints are ranked from smallest (FF-6) to largest (FF-1); FF-15 is excluded because it did not contain insular residual patches. Only footprint FF-12 had buffer area beyond 1400 m. Buffer area fraction = (buffer area/footprint area) and insular area fraction = (insular extent in buffer/total insular extent in footprint).

Spatial association with unburnable cover types

Extent of insular patches within fire footprints was significantly correlated (r= 0.605) with the corresponding extent of unburnable cover type area. This suggests that unburnable area within fire footprints may act as fire breaks and thus result in residual areas. Since there are two major types of unburnable cover (water and non-vegetated, which is primarily bedrock), we examined their spatial association with individual insular patches separately. Correlation of insular residual patch area with bedrock cover type extent was much higher (r=0.503) than with extent of water (r=0.207) within corresponding fire footprints. Across the 17 fire footprints, nearly half the insular patches occurred within 100 m and 25% of all patches bordered bedrock cover (Figure 42a). In contrast, median of insular patch proximity to water was nearly 500 m with only 5% of the patches bordering water (Figure 42b).

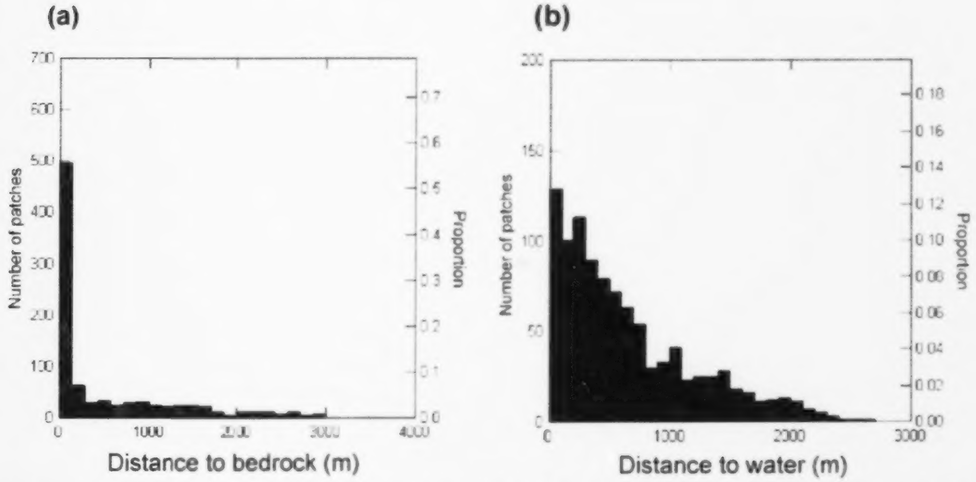


Figure 42. Variability of nearest distances (frequency distribution across all fire footprints) of insular patches to (a) bedrock and (b) water.

The association between insular patch occurrence and proximity to bedrock cover was more pronounced in several fire footprints (Figure 43). Over 40% of insular patches in five footprints (FF-11, FF-12, FF-13, FF-14, and FF-16) bordered bedrock cover. In contrast, insular patch proximity to water was low across all fire footprints.

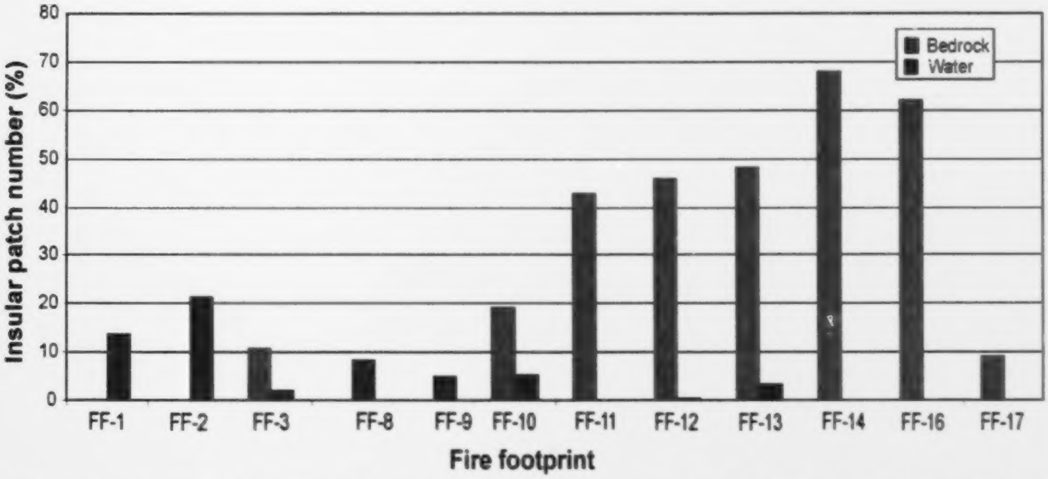


Figure 43. *Juxtaposition of insular residual patches with unburnable cover types (water and bedrock) within fire footprints. Note: Fire footprints FF-5, FF-6, FF-7, and FF-15 did not contain any unburnable cover; and FF-4 had low unburnable cover extent (0.5%) with no insular patches bordering water or bedrock.*

Peninsular residuals

Spatial distribution within fire footprints

We did not assess the spatial distribution of Type 1 peninsular residual patches because they occur *outside* fire footprints. Type 2 peninsular residual patches, by definition, are expected to be biased towards the perimeter of the footprints. Consequently their spatial distribution patterns are known *a priori*. Even though the Type 2 peninsular residual patches mostly occur proximally to the perimeter, their area extends inwards. Figure 44 shows the variability of Type 2 peninsular patch area fraction:buffer area fraction ratio among fire footprints at different distances from their perimeters. It appears that in some footprints, the Type 2 peninsular patch area exceeds expected amounts in the interior, but to a much lower degree than for insular residual patches (Figure 40). Again, it is difficult to generalize any overall trends of occurrence given the high variability among fire footprints in size, shape, and overall residual extent.

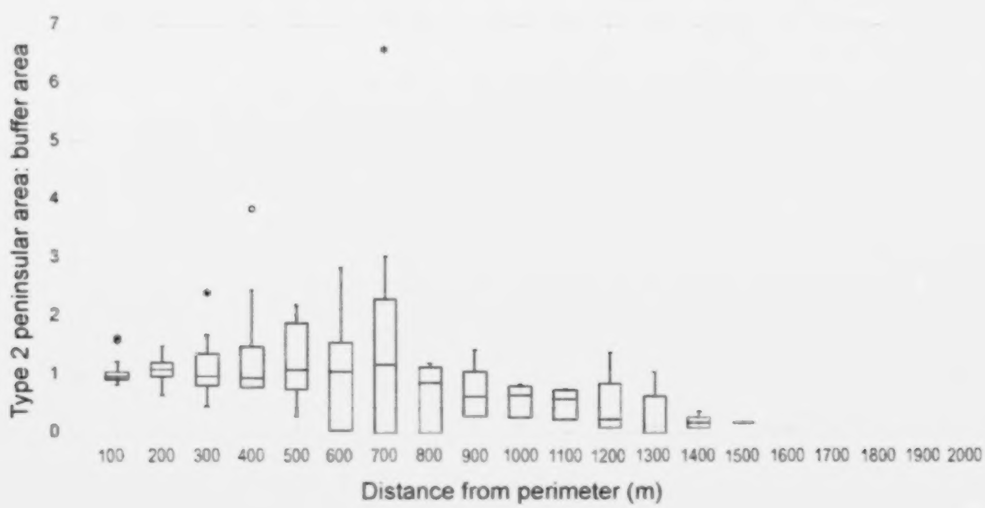


Figure 44. *Variability in the proportionate extent of Type 2 peninsular residual patches in internal 100 m-wide buffers with increasing distance from fire footprint perimeters. Type 2 peninsular area fraction:buffer area fraction = (Type 2 peninsular extent in buffer/total Type 2 peninsular extent in footprint)/(buffer area/footprint area). Only fire footprint FF-12 had buffer area beyond 1400 m. Boxes indicate the interquartile range, lines the median, and whiskers the min-max values. Open outliers (*) are 1.5x interquartile range, and the closed outliers (o) are 3x interquartile range.*

Figure 45 illustrates the Type 2 peninsular area fractions and buffer area fractions at varying distances in all fire footprints. It shows that in large fire footprints these residual patches may extend inwards. Area fraction ratio can be visually interpreted thus: (a) when buffer area fraction (white bars) is less than Type 2 peninsular patch area fraction (black bars) the area fraction is >1 and more Type 2 peninsular residual patch extent occurs at that distance than expected; (b) when buffer area fraction (white bars) is higher than Type 2 peninsular patch area fraction (black bars), the area fraction ratio is <1 and less Type 2 peninsular residual patch extent occurs at that distance than expected; and (c) when buffer area fraction (white bars) is equal to Type 2 peninsular patch area fraction (black bars), the area fraction ratio is 1 and Type 2 peninsular residual patch extent at that distance is as expected. Half of the fire footprints, for example FF-5 and FF-7, had area fractions at <1 at 100 m.

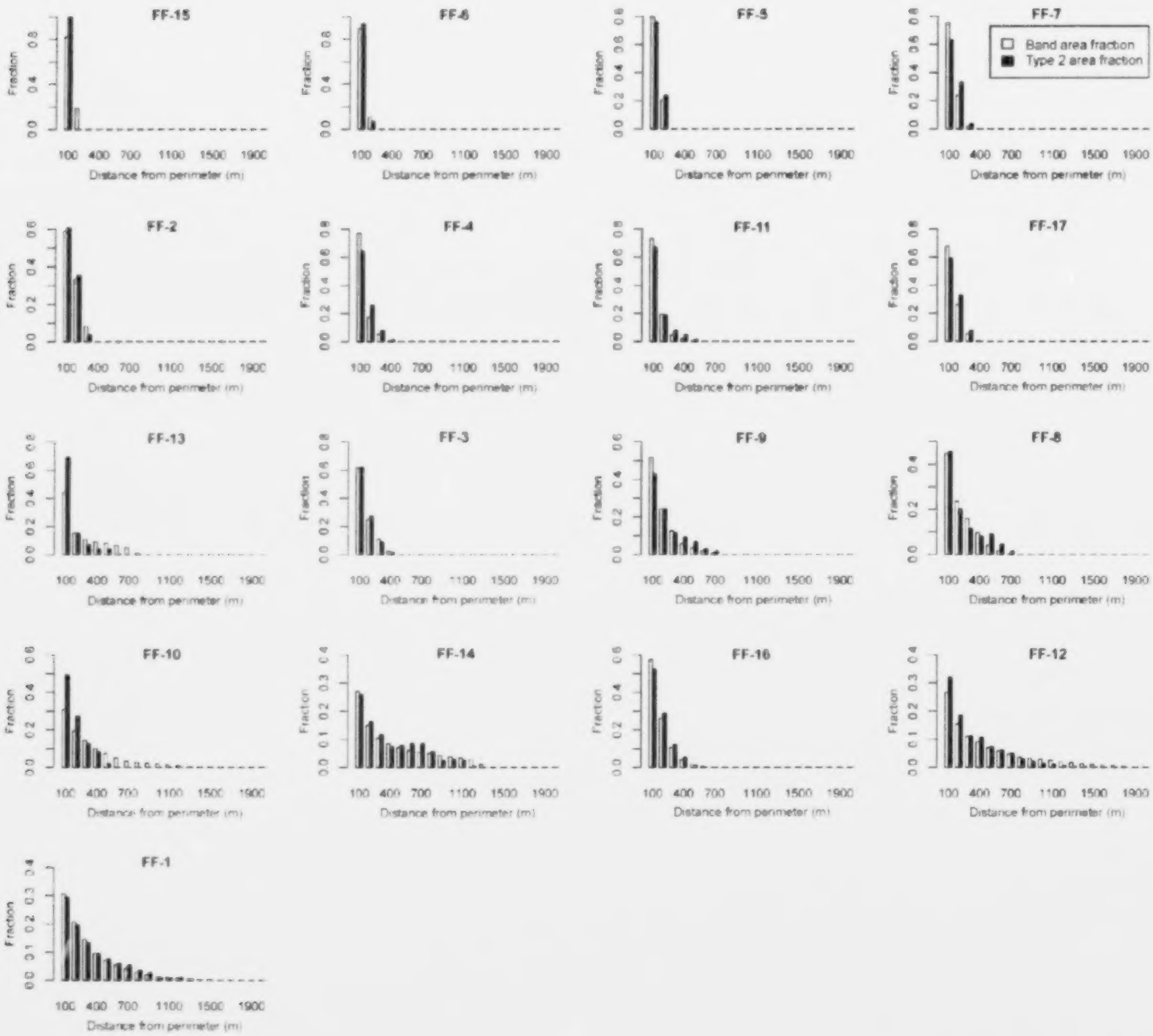


__Figure 45.__ Area fractions at varying distances within study fire footprints. Note: Fire footprints ranked from smallest (FF-6) to largest (FF-1). Only FF-12 had buffer area beyond 1400 m. Buffer area fraction = (buffer area/footprint area) and Type 2 peninsular area fraction = (Type 2 peninsular extent in buffer/total Type 2 peninsular extent in footprint).

Spatial association with unburnable cover types

Extent of Type 2 peninsular residual patches within fire footprints was not significantly correlated (r= 0.121) with the corresponding extent of unburnable cover type area. This suggests that unburnable area within fire footprints did not act as fire breaks for Type 2 peninsular residual patches, overall. Since there are two major unburnable cover types (water and non-vegetated, which is primarily bedrock), we examined their spatial association with individual Type 2 peninsular residual patches separately. Correlation of peninsular residual patch area with bedrock cover type extent was much lower (r=0.044) than with extent of water (r=0.207) within corresponding fire footprints. Across the 17 fire footprints, nearly half of the Type 2 peninsular residual patches occurred within 50 m and 30% of all patches bordered bedrock cover (Figure 46a). In contrast, median of Type 2 peninsular residual patch proximity to water was nearly 180 m with only 5% of the patches bordering water (Figure 46b).

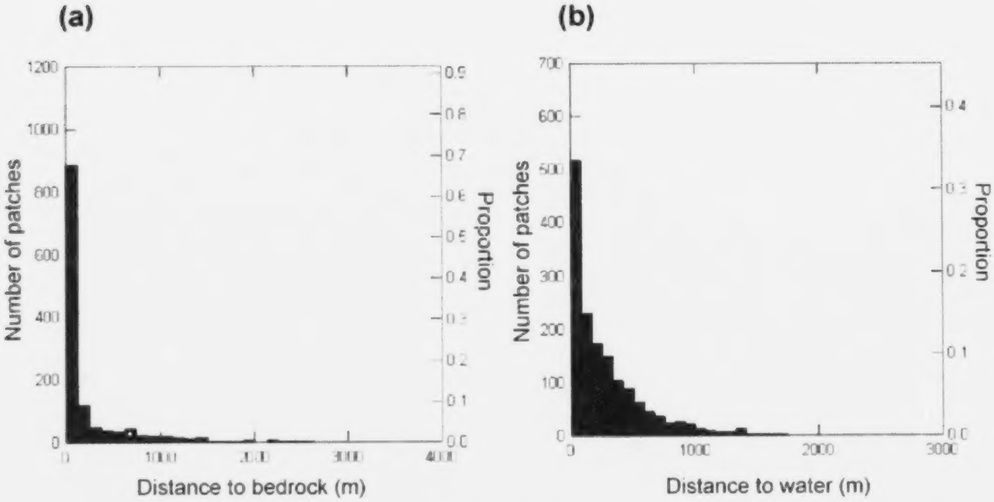


Figure 46. *Variability of nearest distances (frequency distribution across all fire footprints) of Type 2 peninsular patches to (a) bedrock and (b) water.*

The association between Type 2 peninsular residual patch occurrence and proximity to bedrock cover was more pronounced in several fire footprints (Figure 47). Over 40% of Type 2 peninsular residual patches in five footprints (FF-11, FF-12, FF-13, FF-14, and FF-16) bordered bedrock cover. In contrast, Type 2 peninsular residual patch proximity to water was low across all fire footprints.

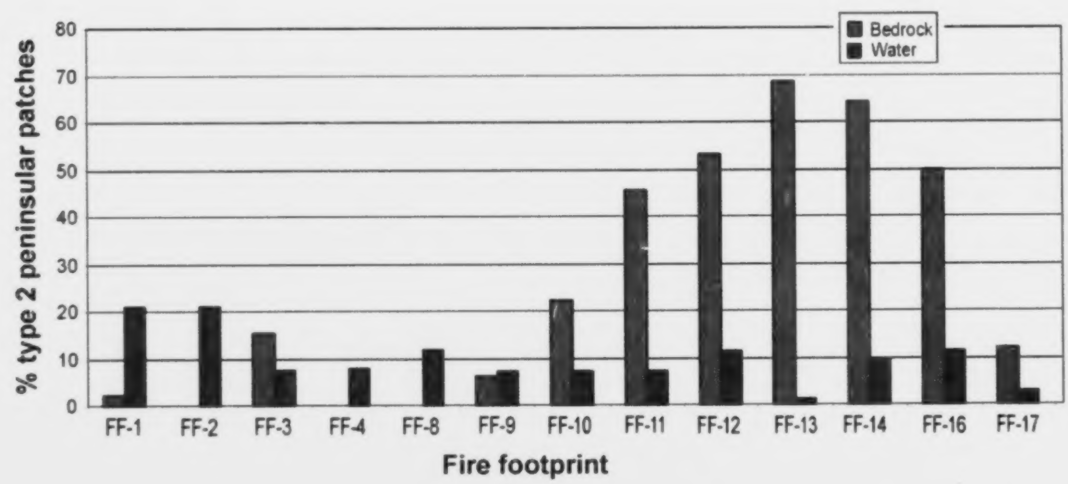


Figure 47. *Juxtaposition of Type 2 peninsular residual patches with unburnable cover types (water and bedrock) within fire footprints. Note: Footprints FF-5, FF-6, FF-7, and FF-15 did not contain any unburnable cover.*

Discussion

The goal of this study was to assess the extent and variability of post-fire residual patches in Ontario's boreal forest in order to assess the directions provided in OMNR's *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide, OMNR 2001). In this context, our objectives in this section are two-fold. First, we summarize our estimates of post-fire residual patch extent and their variability based on the definitions provided in the guide (OMNR 2001) for *insular* and *peninsular* residual patches. Second, we compare our findings with the policy directions provided in the NDPE guide. We do not elaborate on the general state of knowledge of residual patches and specific research needs because these topics were previously discussed by Perera et al. (2007) and are beyond the scope of this report.

Extent and variability of post-fire residual patches

The 17 study fires ranged from 57 ha to 4525 ha: three fires were smaller than 100 ha, three were between 100 ha and 500 ha, three were 500 ha to 1000 ha; and the remainder exceeded 1000 ha. All but one occurred in the Ecoregion 2W, which is in northern boreal Ontario, mostly above 52° N. These study fires are unique because they are natural in all aspects: originated by lightning, occurred in commercially unmanaged forest landscape, and were not suppressed, and thus presented a unique view of residual patch formation under unaltered conditions. However, the absolute numerical values of results we present may not be directly relevant to boreal landscapes in other ecoregions where forest landscapes may be altered, fires are regularly suppressed, and many fires result from human activities. Moreover, we are not certain whether the study fires represent 'normal' or anomalous events with respect to their sizes and intensities due to lack of detailed fire weather information. The 45-yr fire history of Ecoregion 2W showed that most study fires occurred in years when the annual area burned was above average.

The among-fire variability of residual patches was very high, which was evident in high variance estimates in their geometrical, spatial, and compositional characteristics. The possible effects of numerous variables, such as the fire weather of the burn that led to the fire footprint and residual patches, pre-burn cover composition, and spatial patterns of terrain and surficial geology within fires, as well as interactions among them, are complex resulting in this high variability. Given the ensuing variability, the sampling power required to isolate, if even possible, any statistically valid patterns and relationships extends well beyond the sample size of this study. Consequently, statistically valid generalizations and hypothesis testing leading to conclusive statements were not possible. Therefore, we urge the reader to note that the statements below are empirical summaries from 17 fires, which is a very small sample, and must be considered as observations and/or hypotheses, and not as generalized conclusions.

We resorted to the OMNR (2001) definition, which considers insular residual patches as those occurring within fires; at least 20 m away from perimeter, at least 0.25 ha in extent, and composed of vegetated cover. Further, OMNR (2001) defines peninsular patches as those associated with the convolutions of fire perimeter (Type 1) and the residual patches within fires that occur near (within 20 m) the perimeter (Type 2); with both types at least 0.25 ha in extent and composed of vegetated cover. These definitions adopted in this study are not universal, and differ from those in the published literature, for example, Eberhardt and Woodard 1987, Gluck and Rempel 1996, Thomas et al. 1998, Smyth 1999, Kafka et al. 2001, and Perron 2003. This applies to categories of residuals as well as their size delimitations. Published reports address all internal residuals together, not separated by distance to perimeter (Type 2 peninsular and insular) as in this study. When combined, these *internal* residuals (insular and Type 2 peninsular), range from 1.5% to 29.7% in our study fires. Figure 48 illustrates the relative *internal* residual extent in the 17 study fire in relation to values reported in literature (from fires >50 ha to <10,000 ha). However, given the differences in size delimitations as well as compositional definitions of residual patches, we caution the reader not to draw conclusions from these comparisons.

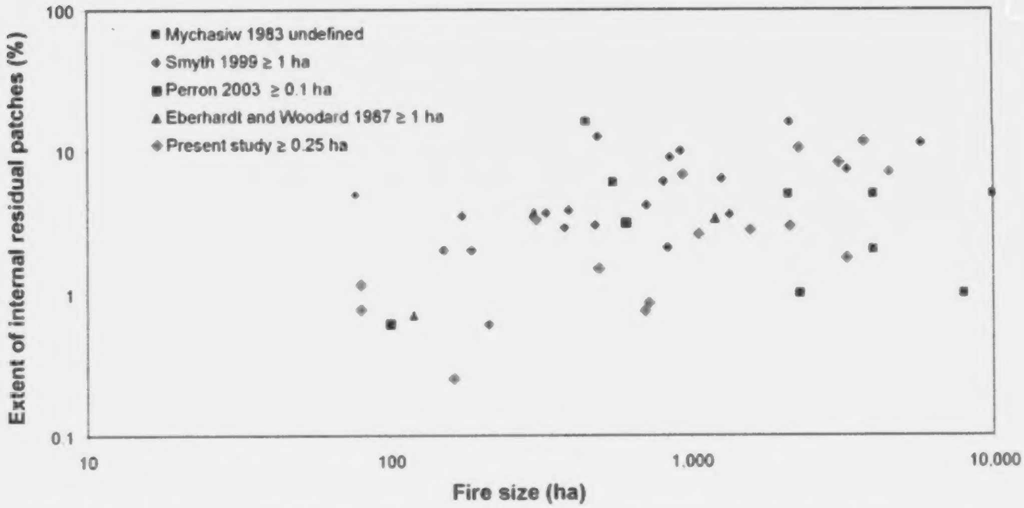


Figure 48. Extent of internal residual (insular and Type 2 peninsular) patches as a percentage of fire size of study fires (◆) compared to those reported in literature (■,♦,■,▲). Note that both axes are log scale and size limits of patches differ among reports.

The total residual extent (using OMNR definitions of insular and peninsular residual patches) varied from 20.7% to 108.7% among the 17 study fires (Figure 49). In all cases, peninsular residuals (Type 1 and Type 2) dominated the residual patch extent. Within peninsular residuals, Type 1 residual patch extent exceeded that of Type 2 in most study fires.

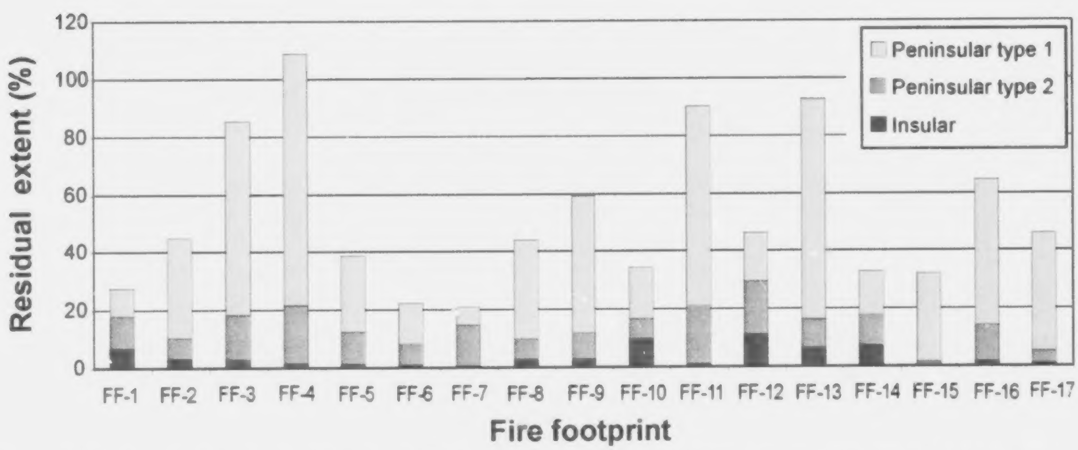


Figure 49. Total extent of residual patches (insular, Type 1 peninsular, Type 2 peninsular) as a percentage of the fire footprint area. Note: We used fire footprints as the base because using burnable area within the footprint as a base for Type 1 peninsular residuals, which occur outside the footprint, is illogical.

Insular residual patches

All but the smallest study fire had insular residual patches. The number of patches per fire ranged from 1 to 259, with a per-fire mean of 59 ± 17. The percentage insular residual area ranged from 0.25% to 11.7%, with a mean of 3.6% ± 0.7%. The 25th percentile was 0.8%, median 2.6%, and the 75th percentile 7.0%.

Most insular patches were small, with a median size <0.5 ha across all study fires, and over 80% of patches were smaller than 1 ha. The largest of all 1007 insular residual patches was 97 ha. Larger fires had higher number of insular patches as well as a higher percentage of insular residual area. Occurrence of insular patches appeared to be spatially independent of one another. However, two trends were observed with respect to within-fire patterns of insular residuals. First, they appeared to be disproportionately common in the interior of most fires, especially the larger ones. Second, they appeared to occur in the proximity of unburnable cover types within fires, especially near the non-vegetated area dominated by exposed bedrock.

The deciduous component was very low in all insular patches. The mean insular residual composition was 44% ± 5.4% conifer, 30.5% ± 4% shrub, 23.1% ± 4.4% wetland, and 1.1% ± 0.5% deciduous. Because we could not estimate the pre-burn land cover composition, relative dominance in residual cover does not necessarily imply post-fire survival patterns or biases.

Peninsular residual patches

We treated the two types of peninsulars separately due to their obvious dissimilarity in origin. All fires had both types of residuals patches, including the smallest. The number of patches per fire ranged from 4 to 105 for Type 1 and from 2 to 263 for Type 2. The per-fire mean number of peninsular residual patches was 39 ± 8 for Type 1 and 90 ± 18 for Type 2.

The area of Type 1 peninsular residual area, as a percentage of the fire footprint area, ranged from 5.8% to 87%, with a per-fire mean of 37.9% ± 6.1%. The 25th percentile was 16.6%, median 34.0%, and the 75th percentile 54.4%. The extent of Type 2 peninsular area was much lower, ranging from 1.5% to 20.3% with a per-fire mean of 11.1% ± 1.3%. The 25th percentile was 6.9%, median 10.8%, and the 75th percentile 15.0%. Combined, both peninsular types occupied from a low of 20.5% to a high of 107.2% of the fire area, with a per-fire mean of 49.4%±6.6. The 25th percentile was 27.2%, median 41.2%, and the 75th percentile 68.4%.

Larger fires had higher number of peninsular residual patches of both types, but fire size was not correlated with peninsular residual patch extent. Type 1 peninsular patches were larger than the Type 2 patches overall. The median patch size of Type 1 peninsulars was <1.5 ha, with over 80% smaller than 10 ha and the largest of all 668 patches was 629 ha. Type 2 peninsular patch median size was <0.6 ha and 80% of patches were smaller than 1.6 ha. The largest of the 1542 Type 2 patches was 220 ha. Occurrence of Type 2 patches within fires extended well inwards, even though their proximal ends were, by definition, within 20 m of fire perimeters. Unlike with insular patches, other patterns were not evident for Type 2 peninsular residual patches, including any association with unburnable cover types.

As with insular residuals, composition of both types of peninsular residual patches was dominated by conifer forest cover followed by shrub and wetland cover types. The deciduous component was low in all patches. The mean composition of Type 1 peninsular residual patches was 44% ± 2.9% conifer, 22% ± 2.5% shrub, 26.1% ± 3.1% wetland, and 3.4% ± 1.6% deciduous. The mean composition of Type 2 peninsular residual patches was 41% ± 4.6% conifer, 30% ± 3.7% shrub, 24% ± 3.8% wetland, and 2% ± 0.6% deciduous.

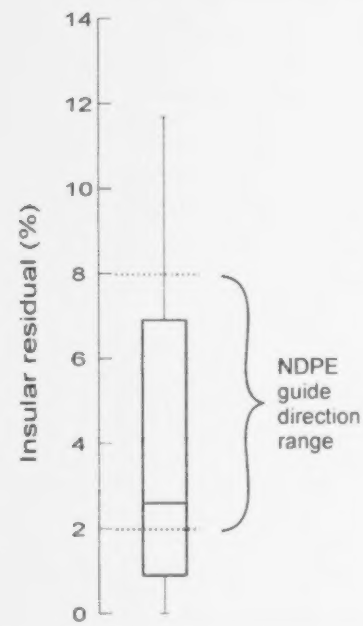
Study results in relation to NDPE guide directions

Below we present our study results in relation to specific directions for residual patches provided in the NDPE guide (OMNR 2001). We remind the reader that our study was conducted in an eco-region that has not been subject to large-scale forest management.

Guidelines for insular residual patch retention

- *range of 2 to 8% of planned disturbance area based on forest cover type (**guideline**)*

The guide's range of values were within the 40^{th} (1.6 %) and 90^{th} (9.2%) percentiles of insular residual patch extent observed in our study. The median (2.6%) and per-fire mean (3.6%±0.7) values of insular patch extent within our study fires were less than the midpoint (5%) of guide directions. The higher value of OMNR's range (8%) exceeded the 95% confidence interval for the study fires (5.7%). Therefore, we conclude that the NDPE guide's direction for insular residual patch extent is within, but marginally overestimates, expected values for natural fires.



Range of insular residual patch extent in the study fires in relation to the NDPE guide direction range.

- minimum patch size –0.25 hectare

Insular residual patches smaller than the NDPE guide direction minimum size limit were numerous in our study fires. The insular residual patch area that was excluded due to the 0.25 ha minimum patch size direction as a percentage of fire size ranged from 2.5% to 6.2% across the fires with a per-fire mean of 3.6%±0.25%. Thus, we conclude that the 0.25 ha size limit for insular patches results in a considerable underestimate of insular residual area, especially in fires with low insular residual extent.

- *well distributed within cutover subject to how fire would naturally distribute (**standard**)*

Insular residual patches were distributed throughout the study fires. Some fires, especially the larger ones, contained higher density of residual patch area in the fire interior. Insular patches were not clustered within fires, but they appeared to be proximal to natural fire barriers such as exposed bedrock and water bodies. Therefore we conclude that insular residual patches are well distributed within natural fires, even towards the fire interior, and hypothesize that their occurrence is spatially biased to natural fire barriers within fires.

- *not available for subsequent harvest (**standard**)*

Longevity of insular residual patches was not assessed in this study.

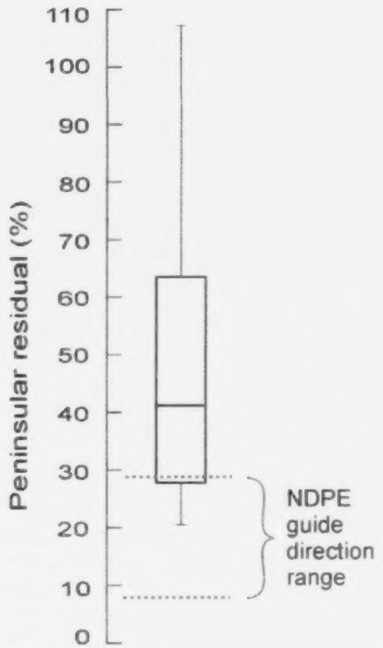
Guidelines for peninsular residual patch retention

• *range of 8 to 28% of planned disturbance area based on forest cover type (**guideline**)*

The guide's range of values fell beyond the lower extreme of the combined peninsular residual patch extent observed in the natural fires of our study. The maximum of the guide's range (28%) is only fractionally higher than the 25th percentile value, and much less than the median (41.2%) and per-fire mean (49.4%±6.6%) of observations from the study fires, and the minimum (8%) was beyond the range of our observations. Therefore, we conclude that the NDPE guide's directions for peninsular residual patch extent is much lower than expected values for natural fires.

• minimum patch size – 0.25 hectare

Many peninsular residual patches smaller than the NDPE guide direction minimum size limit occurred in our study fires. The peninsular residual patch area that was excluded due to 0.25 ha size limit ranged from 2.2% to 11.2% as a percentage of the fire area, with a per-fire mean of 5.4%±0.7%. Thus we conclude that the 0.25 ha size limit for peninsular patches further underestimates peninsular residual area considerably, especially in fires with low peninsular residual extent.



Range of peninsular residual patch extent in the study fires in relation to the NDPE guide direction range.

• *well distributed around edge of cutover subject to how fire would naturally distribute (**standard**)*

Peninsular residual patches were distributed throughout the study fires. Some fires, especially the larger ones, contained higher density of peninsular residual patch area (Type 2) even in fire interior. There was no significant clustering of the peninsular residual patches of either type, and they did not show any significant biases to natural fire barriers such as exposed bedrock and water bodies. However, we cannot conclude on the spatial distribution and occurrence of peninsular patches in natural fires because their locations are, by definition, decided *a priori*.

• *50% of peninsular residual patch area is available for subsequent harvest after 3 metre Free to Grow greenup (**standard**)*

Longevity of peninsular residual patches was not assessed in this study.

Conclusions

We observed a high degree of among-fire variability in post-fire residual patch extent, while larger fires had more residual patches. Peninsular residuals, that occur associated with fire perimeter as defined by the OMNR's Forest Management Guide for Natural Disturbance Pattern Emulation, dominated the residual patch content in almost all study fires. In contrast, the extent of insular residuals, which occur inside fire perimeters, was low among all fires and these were mostly composed of very small patches. As well, insular residual patches were relatively more common in fire interiors, and appeared to be spatially associated with water bodies and bedrock within fires. We did not find differences in composition of residual patches, either among residual categories or among fires. All residual patches were dominated by conifer forest, and included shrub and wetland cover types.

In comparing the study results to Ontario's policy guide directions, we found that the range given for insular residual patch extent is within, but marginally overestimates, the values observed for study fires. In contrast, the guide's direction for range of peninsular residual patch extent is much lower than was observed for study fires. Insular residual patches are well distributed within natural fires, even towards the fire interior, as the policy guide directs. We found that the 0.25 ha size limit for both categories of residual patches underestimates total residual area considerably, especially in fires with low residual extent.

Differences in definitions for residual patches, study geographies, and methods in literature not withstanding, internal residual patch extent found in our study fires are well within the range of those published. Although our sample size was limited to 17 fires and the results may not be directly extrapolated to other landscapes, they all represented absolutely natural conditions: it is rare to find opportunities to study fires that are lightning-caused, occur in unaltered landscapes, and are not suppressed. However, due to lack of supplementary data such as pre-burn cover, detailed fire weather, and terrain, we could not examine causal factors. Some trends we observed in spatial patterns of internal residuals, for example association of residual patches with fire geometry and natural fire barriers, could be considered as hypotheses for future research targeted towards causal mechanisms.

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Appendix 1. Study fire details.

(Source: OMNR[1]):All fires were lightning-caused, and not suppressed. Fire weather indices[2] are those reported at the day of ignition (FFMC= Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Buildup Index, FWI=Fire Weather Index).

MNR fire ID	Year of burn	Fire size (ha)	Fire location		Start date	Out date	Duration (days)	Weather Station	Fire weather indices					
			Lat (°N)	Long (°W)					FFMC	DMC	DC	ISI	BUI	FWI
NIP124	1998	200	53.7264	88.8718	7/5/1998	8/2/1998	28	KAS	79.0	94.0	330.0	1.1	110.0	5.9
NIP144	1998	500	52.6345	87.4506	7/8/1998	8/4/1998	27	WEB	82.0	39.0	256.0	2.6	57.0	8.3
NIP43	1999	1200	53.7345	88.2506	6/13/1999	7/5/1999	22	KAS	83.4	29.0	158.0	2.2	40.0	5.7
SLK82	1999	700	53.8500	89.0141	8/31/1999	9/10/1999	10	BLT	90.1	27.0	297.0	11.3	44.0	22.7
SLK5	2001	80	54.2059	91.3365	7/20/2001	8/13/2001	24	BKN	66.4	14.0	67.0	1.5	18.0	1.9
NIP72	2001	382	53.7968	88.3132	7/20/2001	8/12/2001	23	KAS	89.0	40.0	213.0	7.4	54.0	18.6
NIP73	2001	2250	53.4227	87.9404	7/20/2001	8/12/2001	23	KAS	89.0	40.0	213.0	7.4	54.0	18.6
SLK1	2002	2600	54.2245	91.3817	6/25/2002	8/21/2002	57	BTL	84.8	18.0	80.5	3.6	23.1	6.4
SLK2	2002	90	54.2159	91.4128	6/27/2002	7/12/2002	15	SAC	86.8	29.6	124.5	2.7	37.1	6.6
NIP48	2002	200	53.7607	88.9795	7/5/2002	8/15/2002	41	KAS	89.4	26.6	64.3	8.1	26.6	13.8
NIP47	2002	150	53.8153	88.9365	7/4/2002	8/15/2002	42	KAS	84.5	22.9	56.3	2.7	22.9	4.8
NIP32	2002	2600	53.3783	87.8748	7/1/2002	9/3/2002	64	WEB	81.2	12.5	16.3	10.3	12.2	11.4
RED34	2002	3070	53.0497	93.9413	7/13/2002	8/7/2002	25	SDY	87.1	42.3	211.6	3.8	56.4	11.5
RED56	2002	312	53.0806	94.0076	7/12/2002	7/19/2002	7	SDY	80.3	38.8	202.6	1.5	52.5	4.7
RED27	2002	4536	52.8856	93.6018	7/13/2002	8/7/2002	25	SDY	87.1	42.3	211.6	3.8	56.4	11.5
RED23	2002	4536	52.7781	93.5114	7/13/2002	8/7/2002	25	SDY	87.1	42.3	211.6	3.8	56.4	11.5
RED21	2002	3923	52.653	93.3030	7/13/2002	8/1/2002	19	NLS	89.7	67.0	152.6	6.3	67.0	18.5
NIP38	2002	600	50.8519	86.1405	7/1/2002	8/15/2002	45	NAK	90.4	17.9	111.2	11.0	25.5	17.0
SLK55	2003	16.000	52.2314	89.8920	6/18/2003	7/12/2003	24	CRY	77.9	55.0	237.0	2.0	69.6	7.6
SLK80	2003	900	52.0329	91.5349	7/10/2003	8/12/2003	33	CAT	83.6	8.6	223.1	2.2	15.7	3.0

[1]DFOSS Fire Archive Access Database, Rob Luik, Information Management Specialist, Ministry of Natural Resources, Fire Management Section, 70 Foster Drive, Sault Ste. Marie, ON (705) 945-6748
[2]Based on the Canadian Forest Fire Weather Index System (Van Wagner and Pickett 1985)

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